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Air Flow Patterns within Buildings Measurement Techniques

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Airflow Patterns Within Buildings Measurement Techniques

Air Leakage Measurement Methods

Air Flow Measurement Methods

Measurement Methods Related to Efficiency

Measurements on Ventilation Systems

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Preface

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Programme was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Programme, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRO), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

As one element of the Energy Programme, the IEA encourages research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is encouraging various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programmes, building monitoring, comparison of calculation methods, as well as air quality and inhabitant behavior studies.

The Executive Committee

Overall control of the R&D programme "Energy Conservation in Buildings and Community Systems" is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures all projects fit into a predetermined strategy without unnecessary overlap or duplication but with effective liaison and communication.

Annex V Air Infiltration and Ventilation Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration and Ventilation Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardization of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and, based on a knowledge of work already done, to give direction and firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Germany, Finland, France, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom United States of America.

Annex XX: Optimization of Air Flow Patterns Within Buildings

The prediction and the control of the air flow patterns through the building and in the rooms is necessary to provide an efficient ventilation. Planning methods should allow that prediction from the earliest stage of a project, in order to enhance the comfort and the air quality while saving energy.

Recent developments in measurement and calculation techniques open new ways to study these phenomena. The general scope of the Annex XX is to evaluate the single zone existing models and to help the development of multizone simulation programs. This project has two subtasks:

- Subtask 1: Air and contaminant flow patterns in a room
- Subtask 2: Air and contaminant flows as well between the zones in a building as from or to outside. The scopes of this subtask are to develop new multizone algorithms (e.g. for flow patterns through large openings, for inhabitant behavior, etc); to provide data for the evaluation and the use of computer models and to contribute to the development of new measurement methods.

This handbook is a result of the strong collaboration between the Annex XX, subtask 2 and the AIVC. The latest developments in measurement methods related to ventilation were described by Annex 20 participants and large portions of the Measurement Techniques Guide first published in 1988 by the AIVC and describing the techniques already known at that time were reviewed and integrated, in order to make this handbook more complete.

Countries participating to this subtask are Belgium, France, Netherlands, Sweden, Switzerland, United Kingdom and USA. Moreover, Canada, Denmark, Germany, Finland, Italy, and Norway participated in Annex XX, subtask 1.

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Caution

The material and data presented in this publication is solely intended as a guide to current knowledge of air infiltration and related topics. The information contained herein does not supersede any advice or requirements given in any national codes or regulations, neither is its suitability for any particular application guaranteed. No responsibility can be accepted for any inaccuracies resulting from the use of this publication.

Part I

Introduction

1. Structure of the Handbook

This handbook is concerned with the measurement of those parameters which are important in gaining an understanding of air infiltration and ventilation. The handbook has been designed so that the material suited to your particular level of interest or current expertise, is readily accessible. The flow chart in Figure 1.1 illustrates the structure.

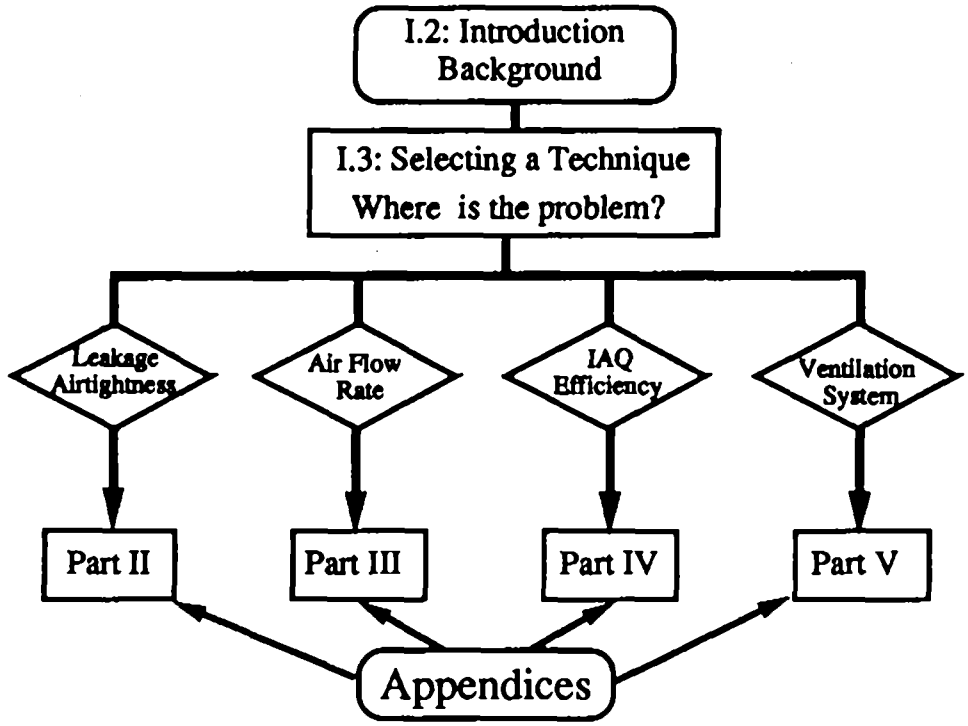

Figure 1.1: Structure of the handbook

The introduction provides a general overview of infiltration and ventilation in buildings. Ventilation studies are discussed and the aims of the handbook outlined.

Part I defines the parameters which are important, presents the reasons why they should be measured and gives a guide to the selection of techniques for particular applications. Summaries of the main techniques available are presented, which are cross referenced with the main body of the handbook.

Part II presents the theory and practice of measuring the airtightness of the building envelope and its components. Leakage location and leakage path distribution within the building is also examined.

Part III presents the theory and practice of measuring air exchange rates and the related contaminant flow rates. Air exchange between a building and the external environment is examined, as is the air exchange between the various internal spaces of a building.

Part IV presents some measurement methods which may be useful to qualify the indoor air and the efficiency of the ventilation system. Measurement of contaminant concentrations are however not described, since another book will be necessary to describe all the possible methods to analyze the thousands of possible contaminants.

Part V Describes measurement methods which are able to qualify a system, namely to measure the flow rates in the ventilation network and to control its tightness.

Appendices are provided either to give information on general tools as units transformations, error analysis, identification methods or to lighten the main text of information which may be useful only to specialists.

A glossary and an index are also provided to facilitate the use of this handbook.

2. Introduction

The provision of an adequate supply of outdoor air suitable for the needs of the occupants is an important aspect of building design and construction. Ventilation (the transport of air into, through and out of a building) can be promoted by natural or artificial forces. It is necessary to understand this process, since it affects both the energy consumption and internal environment of a building. Excessive ventilation will put an undue burden on the building's heating system and may lead to energy wastage, or an unacceptable thermal climate within the building. Insufficient ventilation can cause problems relating to the quality of the air within the building. The internal environment can become uncomfortable or, in extreme cases, harmful to the building occupants. There are a variety of methods by which buildings can be ventilated.

2.1 Infiltration

The only means of ventilation in some buildings is air infiltration. This is an entirely passive process and relies upon the fortuitous leakage of air through various cracks and gaps in the building envelope. Typical leakage paths are illustrated in Figure 2.1.

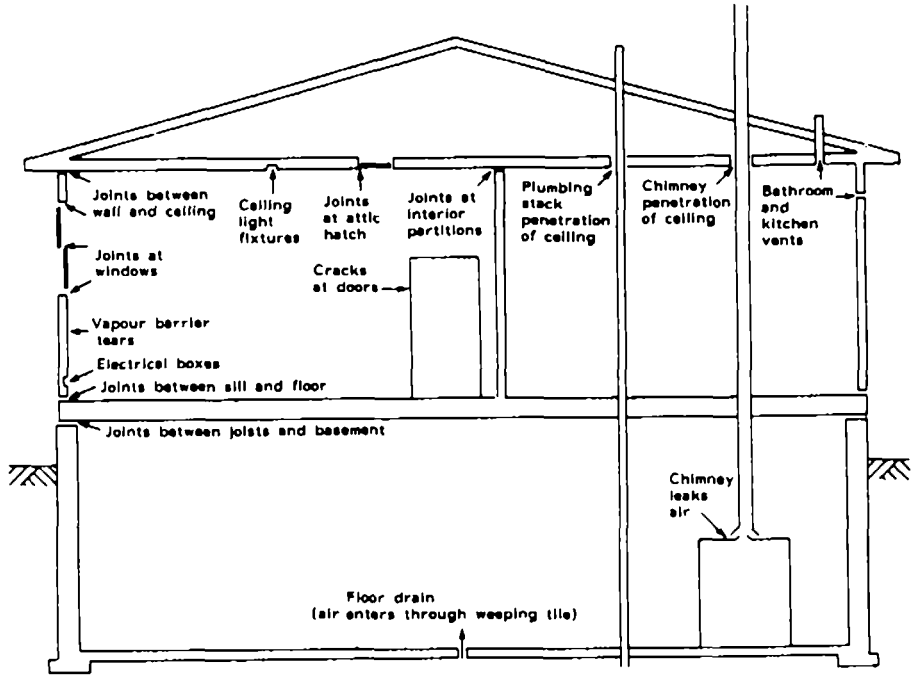

Figure 2.1: Typical leakage paths in buildings [Elmroth and Levin, 1983].

The amount of air entering and leaving the building is dependent upon the pressure differential across the building and the characteristics and distribution of the leakage paths in the envelope. Pressure differentials can be caused by the dynamic action of the wind. In this case air will generally enter through cracks on the windward side of the building and leave through similar openings on the leeward side. A difference in air density due to any indoor/outdoor temperature difference will also produce a pressure differential across the building fabric. This is often referred to as the "stack effect". In a heated building air will rise within the structure, entering low down and leaving higher up. Alternatively it may move in the opposite direction if the air in the building is cooler than that outside. In reality the combined effect of wind and temperature produces complex and variable air flow patterns throughout the building.

2.2 Natural Ventilation

In the infiltration process, the amount of air entering a building is primarily governed by the wind speed, wind direction, indoor/outdoor temperature difference and air leakage characteristics of the building. Because the climate is unpredictable, the specific air flow due to infiltration is a variable parameter which is beyond the control of the occupants. In order to harness the climatic parameters which influence infiltration, buildings can be purposely provided with natural ventilation. This usually consists of controllable apertures which are strategically placed in the building envelope. In this case

the positioning of these openings, and the behavior of the occupants in relation to them, are also factors which influence the rate of air flow into the building.

2.3. Mechanical Ventilation

To obtain more control over ventilation it is necessary to introduce mechanical systems into the building. Air can be removed from a building by a mechanical extract fan or it can be driven into a space using a supply system. Extract ventilation necessitates the provision of sufficient openings in the building envelope, to ensure that the incoming air may easily replace that which is extracted. Similarly, with a supply system the displaced air has to leave the building through any adventitious or purpose provided openings in the building fabric. Whilst to some extent negating the influence of climatic parameters, the correct functioning of mechanical extract or supply systems will still depend upon the air leakage characteristics of the building envelope. A third type of mechanical system is a combination of the previous two techniques, this is the balanced ventilation, in which separate systems are used to supply and extract air from the building. In a totally balanced system there is no net pressure effect due to the operation of the fans, therefore the amount of air entering and leaving the building will be influenced by climatic parameters producing uncontrollable variable pressure differentials across leakage paths in the building fabric.

2.4. Internal Air Movement

The bulk movement of air into and out of a building, whether it is promoted by natural or artificial forces, causes air to flow between the various internal spaces of the building. This exchange of air between internal spaces is of particular importance in relation to the movement of airborne contaminants and moisture from one part of the building to another. An illustration of this would be the effect of air flow between occupied spaces in a dwelling and the cold, unheated roof space above. Here warm moist air could be carried from the living areas and cause condensation problems on the cold internal surfaces of the roof space. Air flow throughout the building cannot be ignored when considering the ventilation process.

2.5. Ventilation Studies

It is clear from the preceding discussion that the ventilation of buildings is an important and complex process, which is influenced by a variety of constructional, behavioral and environmental parameters. It is because of these complexities that ventilation is often regarded as one of the least understood aspects of building physics. In recent years research and development in two major areas, mathematical modelling and measurement techniques, has led to a greater depth of knowledge in the field of air infiltration and ventilation. Theoretical methods are now available which enable air exchange rates, both with the environment and between the internal spaces of the building to be evaluated. If these models are to be effectively applied, considerable computational power and large amounts of input data must be used. Alternatively simplified calculation techniques can be utilized. These require less effort to perform but the output is correspondingly limited. Mathematical modelling methods have previously been examined in detail by the Air Infiltration and Ventilation Centre *[Liddament, 1986]*.

2.6. Measurement Techniques

A great deal of effort has been devoted to the development of measurement techniques for air infiltration and ventilation. Several of these techniques have been previously examined by the International Energy Agency as part of a wider programme concerning residential building energy analysis *[IEA Annex III, 1983]*. Now techniques are available which enable the flow rate of air into a building, under normal environmental conditions, to be evaluated. Measurement methods also exist which allow the air exchange rate between the internal spaces of a building to be quantified. Evaluation of the overall airtightness of the building shell has become routine and, in some countries, mandatory. The location and distribution of air leakage sites can be determined, and the air leakage characteristics of specific building components or leakage paths can be evaluated.

Measurement techniques are the fundamental means of acquiring a greater understanding of air infiltration and ventilation, in that they enable primary data to be obtained from the evaluation of existing structures. This document examines, in detail, many of the measurement techniques used for air infiltration and ventilation studies. The broad aims of the handbook are to identify the parameters which require evaluating, indicate the variety of measurement techniques which are available, provide detailed information about several techniques, and offer advice regarding the selection of a technique for a particular application.

3. Selecting a Technique

This chapter intends to give the information which may help the user in choosing the measurement techniques able to solve his problems.

3.1. Strategy of Selection.

Measurements in buildings are useful for two essential purposes, these are:

1- for commissioning a new building or part of it, in particular its ventilation system, to check the correct operation of the new system, to set controls and dampers and to locate faults.

2- to detect possible malfunctions in existing buildings (e.g. sick buildings) and to diagnose their causes.

In both cases, malfunctions have an effect not only on comfort and indoor air quality, but also on the energy needs of the building, as well for heating or conditionning the air as for the fans.

These objectives may be applied to three different domains: the building and its elements, the indoor air quality and the ventilation system. More precisely, measurements can give the following information:

To characterize the **building or building elements**:

- locate the main leakages;
- measure the total leakage of the building for a given pressure difference;
- measure the leakage characteristics of the building or of building elements;
- measure the leakage distribution in the building.

To characterize the **indoor air quality** and the **room-ventilation system**

- determine the age of the air at different locations in the room;
- derive a map of the contaminant concentration resulting from contaminant sources, ventilation system and air flow pattern.
- determine the air exchange efficiency or the fresh air distribution within the room;
- determine the ventilation efficiency, that is the efficiency in extracting the contaminants generated in the room.

To characterize **the ventilation system**:

- measure the global air change rate in a room, a zone or a building;
- measure the air flow rates between rooms or zones and between rooms or zones and the outside;
- determine the flow rate in the air ducts (inlet, extraction, short-circuits);
- determine the efficiency of the ventilation system, that is the ratio of the system supplied fresh air to the total fresh air flow rate including infiltration.

Each particular need cited above requires its own measurement methods. Hence the real question is not "Which measurement method shall I use?" but "**What information do I really need?**". Thus the starting point is to define clearly the problem to be solved. Once this is done, the choice of measurement method is much easier.

The parameters which may be obtained through each measurement technique are presented in section 3.2 and the detailed selection method is presented in section 3.3.

3.2. Measurable Parameters

This section examines those parameters which are of interest in air infiltration and ventilation studies.

3.2.1. Air Leakage Characteristics

The rate of air flow is dependent upon a range of variable influencing factors. A basic approach in air infiltration and ventilation studies and in building evaluation is to try to negate the influence of these variable factors and evaluate the air leakage characteristics of the building fabric only.

Leakage paths occur in both the external envelope and internal partitions of a building. If there is a pressure difference across a leakage path, then air will flow through it. Under normal operating conditions, pressure differences are caused by the wind, indoor/outdoor temperature difference and mechanical ventilation systems. In order to evaluate the leakage performance of the building envelope

mechanical ventilation systems. In order to evaluate the leakage performance of the building envelope it is these variable pressures which must be eliminated.

Evaluation of the air leakage characteristics of a structure consists of superimposing a known artificial pressure difference across the envelope or component and measuring the air flow rate through it.

In any building there are many potential leakage sites, these may be either adventitious or intentional. A knowledge of the location of these sites is a first step towards evaluating the envelope in terms of air leakage. Several techniques exist which enable leakage sites to be located. These techniques are discussed in part II.

In order to characterize the leakage performance of the building completely, it is necessary to determine quantitatively the relationship between the air flow through, and the pressure differential across, the leakage paths. The actual relationship may depend upon the nature of the leakage path. The building envelope can be examined in its entirety or, if more detail is required, relationships for individual building components or leakage paths can be developed.

3.2.2. Multizone Air Flow Rates

The bulk movement of air into and out of a building causes air to flow between the various internal spaces of that building and between these internal zones and the external space, which can be also considered as a zone. These air flows are, in terms of both rate and direction, a variable parameter dependent upon construction details, ventilation system operation, climatic effects and occupancy patterns. This variable air movement plays a vital role in heat transfer and in the distribution of internally generated pollutants throughout the ventilated space.

Often ventilation requirements are derived by making the assumption that both the ventilating air and pollutant are uniformly mixed throughout the building. Such conditions may not prevail in practice. Pollution sources are often located at a particular point in a large interior space or confined to an individual room within a building. The pollution from a particular source may not be evenly distributed throughout the ventilated space. In this case it would be incorrect to treat the entire building as a single enclosed space.

A consequence of internal air movement is pollution migration. This can be detrimental to either the fabric or occupants of the building. In hospitals, for example, air flow directions must be kept under control, in order to prevent the transport of odors and germs from one area to another. A well known phenomenon is the migration of humidity from moisture production zones, such as kitchens, to unheated areas, such as bedrooms or attics (see Figure 3.1). This can cause condensation and mould growth problems. Therefore, in order to gain a complete understanding of the ventilation behavior of a building, it is desirable to know the rate of air exchange between the various internal spaces of the structure.

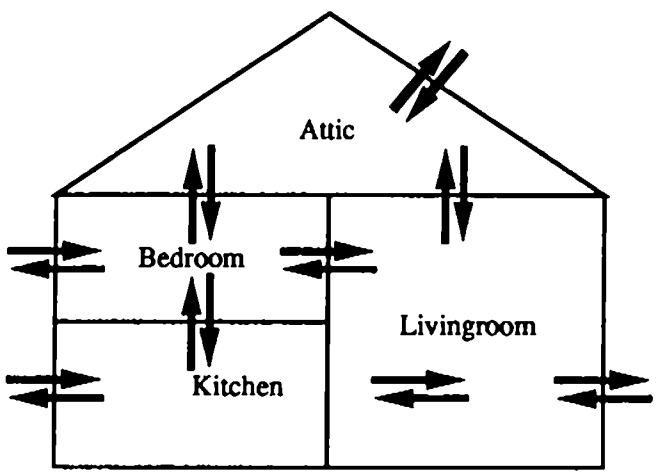

Figure 3.1: Air flows in a building divided into 4 zones.

The techniques used to measure these interzonal air flows involve the use of an inert tracer gas which is released into the building. However, because of the complex nature of these air flows, it may be necessary to utilize sophisticated equipment and more than one tracer gas. The measurement of interzonal air flows using these methods is discussed in further detail in part III, whereas the techniques for the determination of the air flow rates in a mechanical ventilation system are presented in part V.

3.2.3. Air Change Rate or Specific Air Flow Rate and Nominal Time Constant

The exchanges between the building and the external space, that is the amount of air which enters and leaves a building is of fundamental importance in air infiltration and ventilation studies. One convenient way of quantifying this air flow rate is to relate it to the volume of the actual space (whole house volume or room volume). The **air change rate** or the **specific air flow rate** of a building is a measure of the bulk movement of air into and out of a space and is defined as the volumetric rate at which air enters (or leaves) a space divided by the volume of the space. Often the air change rate is expressed in air changes per hour (ACH). One air change per hour means that the total volume of air passing through an enclosed space in one hour is equal to the volume of that space (see Figure 3.2).

Speaking in terms of energy use, one air change means that a volume of air corresponding to the indoor volume is exchanged, thus heated or cooled, with the corresponding energy consumption.

However, speaking in terms of indoor air quality, this does not necessarily mean that the air is completely renewed (or the contaminants completely removed) after one hour. The time it takes to exchange (replace) the air in the actual space is dealt with in Part IV of the handbook.

The **nominal time constant** τ_n is the reciprocal of the specific air flow rate, that is the ratio of the volume of the space to the air flow rate going through that space.

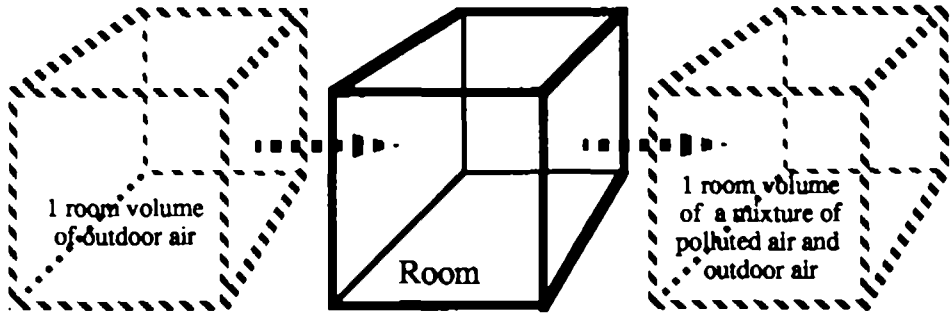

Figure 3.2: Schematic illustration of the air change rate or specific air flow rate.

The nominal time constant has several physical interpretations. The average residence time of the supply air is equal to the nominal time constant. Furthermore, the time it takes to evacuate a contaminant present in an enclosure (the contaminant source being eliminated) is determined by the nominal time constant. For example, assuming complete mixing, hence homogeneous contaminant concentration, it takes a time interval equal to five times the nominal time constant to eliminate 99 % of a contaminant.

The air change rate of a building has major implications with regard to both indoor air quality and energy consumption. The internal environment of a building must satisfy the physiological needs of the occupants. Fundamentally this implies that the occupants should be able to breath in a normal and comfortable manner. Respiration requires the intake of oxygen. Human tolerance to variations in the percentage of oxygen in air is relatively high and it is unlikely that a harmful shortage of oxygen will ever occur in occupied buildings. For a given level of activity, breathing rate is primarily controlled by the concentration of carbon dioxide in the lungs. Outdoor air contains about 0.03% carbon dioxide by volume. If inhaled air contains 2% carbon dioxide, the depth of breathing increases. If concentrations reach 3-5%, respiration becomes difficult and the atmosphere is noticeably unpleasant. Concentrations above 6% are considered to be dangerous.

There are two basic approaches for the control of internal pollutants; these are:

- removal or reduction of the pollutant source
- dilution by ventilation once the pollutant is airborne.

Since exhaled air contains carbon dioxide, outdoor air must be supplied to occupied spaces in order to dilute the internal concentration to an acceptable level. This air flow rate represents a basic ventilation requirement for occupied buildings.

In addition to carbon dioxide, there are a number of other internally generated contaminants which pollute indoor air. In general, each pollutant requires a different ventilation rate to ensure adequate dilution and removal. The amount of fresh air supplied to a building must at all times exceed the rate necessary to disperse the pollutant requiring most ventilation. Actual building ventilation requirements

ventilation requirements is given by IEA-ECB Annex IX *[IEA ANNEX IX, 1987]*.

In all cases where heating or cooling is needed, the necessity for outdoor air gives rise to significant energy losses. Any increase in standards relating to the thermal insulation of buildings tends to increase this significance, as the heat loss due to conduction is diminished. In the case of cold air entering a heated building, and assuming the need to maintain the thermal environment within the structure, the ventilation energy loss H is given by Equation 3.1.

$$H = \rho\, Cp\, n\, V\, (T_i - T_0) \quad [W/K] \tag{3.1}$$

where

ρ is the density of air [kg/m^3]

C_p its specific heat capacity [J/kg.K] or [Wh/kg.K]

n the specific air flow rate or air change rate [s^{-1}] or [h^{-1}]

V the volume of space [m^3]

T_i the internal temperature [K or °C] and

T_0 the external air temperature [K or °C].

On substituting typical values for heat capacity and density, Equation 3.1 reduces to the approximate expression:

$$H = 0.33\, n\, V\, (T_i - T_0) \quad [W/K] \tag{3.2}$$

where n shall be expressed in [h^{-1}]

Unless heat recovery is utilized, the heat load due to any ventilation requirement is unavoidable. If, however, the amount of air entering a building exceeds that required to control the internal environment, an unnecessary burden is placed on the heating system. At the design stage, the principal task is to minimize energy consumption whilst maintaining good indoor air quality. In order to achieve this goal, mathematical methods have been developed and these are now capable of playing an important role in the determination of suitable ventilation strategies *[Feustel and Dieris, 1991]*. Air change rate is a variable parameter which is dependent upon climatic influences, constructional details, and occupant effects. For existing buildings, practical methods can be utilized to evaluate the air change rate of a building under normal climatic and usage conditions. Measurements of air change rate involve releasing an inert tracer gas in a building and monitoring its concentration with time. Several distinct techniques exist and these are discussed in Section 2.1. These measurements enable a building to be assessed in terms of its ability to provide adequate ventilation for its occupants, and allows the actual energy loss due to infiltration and ventilation to be evaluated.

3.2.4. Efficiency and effectiveness

The purpose of any natural or mechanical ventilation system is to replace the polluted air by fresh air in order to satisfy the needs of occupants. Ventilation should fulfill this task without using too much energy. Several efficiency concepts are used to qualify how well the task is fulfilled; these include:

- **air exchange efficiency**: this is a measure of how effectively the air present in a room is replaced by fresh air from the ventilation system, that is how close the nominal time constant is to the time needed to completely change the air.
- **ventilation effectiveness**: this expresses how quickly a contaminant is removed from a given location or from a given space. It is the ratio of the contaminant concentration at the location of interest to the concentration in the exhaust air.
- **efficiency of a ventilation system**: this expresses the portion of fresh air which is introduced into the space through the ventilation system.

The techniques to measure the first two efficiencies are presented in part IV, whereas the measurement of the efficiency of the ventilation system is described in part V.

3.2.5. Contaminants Concentrations

Internal pollutants are defined as any constituent of indoor air which has a detrimental effect on the health of occupants, reduces amenity, or damages building fabric. Typical indoor contaminants include moisture, gaseous and particulate pollutants from indoor combustion processes (e.g. cooking, heating, tobacco smoking), toxic chemicals and odors from cooking and cleaning, odors from humans, and a wide assortment of chemicals released from building materials and furnishings. Among the less common pollutants are the diverse range of odors, chemicals and particulates which are produced

within industrial and commercial buildings.

Contaminants are assessed in terms of their source strength, external and internal concentrations, discomfort effects and toxicity. Measurement methods to determine these quantities include *[IEA ANNEX IX, 1987]* chemical analysis methods, physical analysis (spectrometers, gas chromatographers) and panel judging of odors *[Fanger, 1988]*.

It is not possible to present in this handbook all these methods for the measurement of every possible contaminant. However, some analysis methods which are presented in part III may be used to measure some common contaminants such as moisture or carbon dioxide.

3.3. Application and Selection

This section deals with the selection of measurement techniques for particular applications.

3.3.1. General Process of Selection

The process of selecting a measurement technique takes place in three broadly defined stages.

1 **Application, Objective of Measurements:** The first task is to clearly define the purpose for which the measurement is required, that is to clearly define the problem to be solved or the questions to be answered.

2 **Parameters:** The specific parameters to be measured must then be decided upon. Section 3.2 presents more detailed information regarding the parameters covered by this handbook.

3 **Selection:** Several techniques may be available for the measurement of the required parameters. As well as technical considerations, the final choice of technique may often be affected by more mundane issues such as available finance, time allocation, manpower and personnel expertise.

3.3.3. Selecting a Measurement Technique

In order to aid the selection of a measurement technique for any given application, two series of tables are presented. Tables 3.1 to 3.4 describe several applications which require air infiltration and ventilation rate measurements to be performed. The applications are classified under the following general subject headings:

Building diagnosis	Table 3.1.
Commissioning	Table 3.2.
Conformity to standards	Table 3.3.
Evaluation of mathematical models	Table 3.4.

A brief description of each application is given and the parameters requiring measurement are presented. Finally guidance as to the type of technique(s) suitable for each application is provided.

Tables 3.5 to 3.11 present summaries of the main measurement techniques examined by this handbook. The techniques are grouped under the following general headings:

Leakage location and qualitative methods	Table 3.5.
Building envelope airtightness methods	Table 3.6.
Building component airtightness methods	Table 3.7.
Air change rate methods	Table 3.8.
Interzonal air flow methods	Table 3.9.
Air flows in ducts	Table 3.10.
Age of air measurement methods	Table 3.11.

For each technique a list of equipment is given and the actual measured quantities are presented. Specific factors which may govern the selection of a particular technique are indicated, and each technique is cross-referenced with the main body of the handbook.

The information presented in this Section and Tables 3.1 to 3.11 does not necessarily preclude the use of other techniques for these or any other infiltration and ventilation related applications. For fundamental research, any method, even those which are not known today, may be used and no recommendation is given here for the selection of methods for research purpose.

Table 3.1: Building diagnosis

The purpose is to obtain more information on an existing building in order to know its energy flows, to plan retrofit measures, to troubleshoot problems in the ventilation system or to find the causes of indoor air quality problems.

Objective	Evaluated Parameters	Technique and reference†
Energy diagram of a building (Sankey diagram)	Energy use	*[Fracastoro, Lyberg 1983]*
	Indoor temperature	*[Fracastoro, Lyberg 1983]*
	Outdoor temperature	*[Fracastoro, Lyberg 1983]*
	Solar radiation	*[Fracastoro, Lyberg 1983]*
	U-Values	*ISO-9869*
	Air change rate	Single tracer III
	Efficiency of boilers	
Retrofit an existing building	Leak detection	II.2.3
	Air tightness	II.2.2 and II.2.4
	Air flows in HVAC	V.3
	Energy use	*[Fracastoro, Lyberg 1983]*
	If the energy use is too high, determine the energy diagram.	
Troubleshooting in ventilation system	Air flow rates	V.3
	Airtightness	V.5
Indoor air quality	Diseases	Questionnaire, odor *[Fanger, 1988]*
	Contaminant concentrations	
	Ventilation efficiency	IV.5

Table 3.2: Commissioning

The purpose of these measurements is to verify the performances of the building and its ventilation system, and to assist in adjusting ventilation controls and dampers.

Objectives	Evaluated Parameters	Technique and reference
Verifying and adjusting the ventilation system	Air flow rates	V.3
	Airtightness	V.5
Verifying the airtightness of the building fabric	Air leakage	II.2.2

Table 3.3: Compliance to Standards

The purpose of these measurements is to determine if the examined building or component complies with relevant standards.

Objective	Evaluated Parameters	Technique and reference
Ventilation rate standards	Air change rate	III
	Air change efficiency	IV.5
Envelope airtightness standards	Air Leakage	II.2.2
Components airtightness standards	Air Leakage	II.2.4

† I.References in italics are not part of this Handbook but quoted in the bibliography.

Table 3.4: Evaluation of Mathematical Models

The objective of these measurements is to provide input data for infiltration and ventilation simulation codes. Once debugged and evaluated with simple benchmarks, these codes should be evaluated by the comparison of their results with accurately measured test cases.

Category of data	Evaluated Parameters	Technique and reference
Input data	Meteorological data	*[Fracastoro, Lyberg 1983]*
	Indoor temperatures	*[Fracastoro, Lyberg 1983]*
	Pressure coefficients	*Wind tunnel experiments*
	Leakage distribution	**II.2.4**
	Inhabitant behavior	*Record windows and doors openings and fans switching. [Roulet et Al, 1991]*
	Network characteristics	Flow/pressure drop Discharge coefficients
	Fans characteristics	Flow/pressure
Validation data	Input data with high accuracy	See above
	Air flow rates	**III**
	Pressure differences	**II.3.1**

Table 3.5.: Leakage Location and Qualitative Methods

See sections II.2.3 and II.4.2

Technique	Equipment	Measured quantities	Factors affecting selection.
Acoustic Detection method	Sound source Sound meter	Sound intensity at locations around the building	Low equipment cost. Experience required to use the method effectively. Prone to spurious noise.
Infrared imaging Depressurization	IR camera Depressurizing equipment	Surface temperature distribution	High equipment cost. Information obtained quickly. Skill required to interpret thermographs. Depressurization enhance the sensitivity.
Smoke leak Visualization	Smoke production device Depressurizing equipment	Examination of smoke movement	Low equipment cost. Simple to use but skill required to use the method effectively. Time consuming unless limited investigation.
Bubble visualization	Helium supply Bubble generator Soap solution Depressurizing equipment	Examination of Bubble movement	Medium equipment cost Good for laboratory use Experience required to use the method effectively
Pulse pressurization	Microphone or fast recording manometer	Pressure variations	Still under development

Table 3.6.: Building Envelope Airtightness Methods
See sections II.2.2 and II.4.1

Technique	Equipment	Measured quantities	Factors affecting selection.
DC Pressurization Internal Fan	Suitable air handling system in the building Means of measuring flow rate Differential manometer.	Air flow rate Pressure differential across the envelope Building volume and/or envelope area	Ideal for large, mechanically ventilated buildings. Requires knowledge of HVAC Achievable pressure differential may be limited
DC Pressurization External Fan	Fan with panel Fan flow controller Flow rate measurement device Differential manometer.	Air flow rate Pressure differential across the envelope Building volume and/or envelope area	Commercially available equipment Blows large volumes of air through the building.
AC Pressurization	Door panel with volume drive bellows Monitor Manometer Control hardware and software	Bellows volume change Pressure variation in the building Building volume and/or envelope area	Operates at low pressures Commercially available Displaces small volumes of air through the building. Less subject to wind. Does not measure large leaks.

Table 3.7.: Building Component Airtightness Methods
See sections II.2.4 and II.4.3

Technique	Equipment	Measured quantities	Factors affecting selection.
Direct component testing	Sealing box Fan with controller Flow rate measurement device Differential manometer.	Air Flow rate through component Pressure difference across component Component dimensions	Good for building having a large number of replicated components. Time and skill required to use the method.
Indirect component testing with taping	Pressurization equipment (see table 3.6) Sealing products as plastic sheet, tape.	Air Flow rate through envelope Pressure difference across envelope Sealed components area	Does not apply to components which cannot be sealed. Time and skill required for efficient sealing .
Multi-fan testing	Two or more sets of pressurization equipment Pressure differential measurement and control devices	Air Flow rate through main test fan Pressure difference across test components and across other partitions	Skill required to balance pressure differentials More than three equipments may be required in complex buildings. Susceptible to wind effects.
Combination of pressurization and tracer gas	Pressurization equipment (see table 3.6) Tracer gas equipment (See table 3.8)	Air Flow rate through fan Pressure difference across envelope Tracer gas concentrations	Measure inter-zonal leakages Several components can be measured simultaneously with several tracers.
Stack effect method for high rise buildings	Hot wire anemometer Three or more thermometers 3 or more differential manometers	Flow trough a large opening Temperature and pressure differentials at three or more levels	Low cost equipment Suitable for high rise buildings Limited available information Susceptible to meteorological conditions.

Table 3.8.: Air Change Rate Methods

The purpose is to measure the air flow rate entering a single zone and/or the resultant air change rate or specific air flow rate.

Technique	Equipment	Measured quantities	Factors affecting selection.
Pulse injection Decay method	Tracer gas, injection device and mixing fans Air sampling system Gas analyzer Recorder or data logger	Tracer concentration versus time Zone volume	Equipment commercially available Air change conditions are averaged over the measurement period.
Constant injection rate	Decay equipment + Constant injection rate control device	Tracer concentration versus time Tracer flow rate Zone volume	Allows the estimation of variable air change rate Risk of high tracer concentration.
Constant concentration	Decay equipment + Injection rate control system, including data logger, computer and software.	Tracer concentration versus time Tracer flow rate Zone volume	Allows continuous measurement of variable flow rate. Allows the combining of several zones. Higher material cost.

Table 3.9.: Interzonal Air Flow Methods

The purpose of these measurements is to determine interzonal air flow rates and internal-external air flow rates. All these methods require skill and knowledge of rather complex mathematics.

Technique	Equipment	Measured quantities	Factors affecting selection.
Single tracer	Depends on method See table 3.8	Tracer concentration versus time, Tracer flow rate Volumes of the zones.	Requires several sets of measurements during which conditions remain constant
Multi tracer active sampling	Several tracers Corresponding gas analyzer(s) Several injection devices Sampling system in each zone Data logger, computer, software	Tracer concentrations for each tracer in each zone Tracer flow rate Volumes of the zones.	Can provide continuous information even with variable air flow rates. Practical with up to 5 tracers Mainly used for research purposes
Multi tracer passive sampling	**In each zone:** one tracer emitter one or two passive samplers **In the lab:** Desorber, Special gas chromatographer Data logger, computer, software	Tracer doses for each tracer in each zone Volumes of the zones.	Provides average information on flow rates when they do not vary much. With variable air flows, provides good information on contaminant spreading. Practical with up to 7 tracers Needs small tracer amounts Can be used for many measurements in the field.

Table 3.10: Air flows in ducts

Technique	Equipment	Measured quantities	Factors affecting selection.
Flow rate in a duct Velocity method	Hot wire anemometer Means to locate the anemometer in the duct	Air speed at several locations in the duct. Low cost.	Requires straight ducts Time consuming
Flow rate in a duct Tracer gas method	Tracer gas Injection device Sampling tube Gas analyzer Recorder or data logger	Tracer concentration versus time Tracer flow rate or doses	Requires good mixing Best for curved ducts and fans Relatively fast
Flow rates in a ventilation network	Same as for single duct but several tracers or several sets of measurements	Tracer concentrations versus time Tracer flow rates	Requires good mixing Can provide all flow rates in one measurement.
Efficiency of the ventilation system	Same as for flow rates in ventilation network	Tracer concentrations versus time Tracer flow rate	Result directly deduced from the measurements on network.
Air tightness of a duct or network	Sealing products Differential manometers Flow metering device	Air flow rate Differential pressure	Result depends on careful sealing.
Leak detection in ducts	Smoke generator Sealing products	Observation of smoke leaving the ducts	Only the visible ducts can be inspected.

Table 3.11: Age of Air Measurement method

These measurements are useful for indoor air quality evaluation.

Technique	Equipment	Measured quantities	Factors affecting selection.
Local mean age of air	Tracer gas Injection device Sampling device Gas analyzer	Tracer concentration versus time	Similar to single tracer decay method for air change rate.
Mapping experiments	Tracer gas Injection device Sampling system Gas analyzer	Tracer concentration versus time Coordinates of sampling locations	Similar to single tracer, multi-zone decay method for air change rate.
Room mean age of air	Tracer gas Injection device Sampling system Gas analyzer	Tracer concentration versus time in the exhaust duct.	Similar to local mean age of air.
Air change efficiency	Tracer gas Injection device Sampling system Gas analyzer	Room mean age of air Nominal time constant	See "Room mean age" and "Air change rate"
Ventilation efficiency	Sampling system Gas analyzer	Concentration of contaminants	Difficulty depends on the contaminant.

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Part II
Air Leakage Measurement Methods

Symbols and Units

A	area, cross section	[m^2]
A_f	cross section of a float.	[m^2]
A_L	equivalent leakage area	[μ^2]
a	coefficient representing the laminar part of the quadratic law	[Pa s/m^3]
b	coefficient representing the turbulent part of the quadratic law	[Pa s^2/m^6]
c	coefficient representing the pressure difference at zero flow in the quadratic law	[Pa]
C	leakage coefficient	[m^3s^{-1} Pa^{-n}] or [$kg.s^{-1}$ Pa^{-n}]
C_o	leakage coefficient at standard conditions (e.g. 20 °C and 101.3 kPa.)	[m^3s^{-1} Pa^{-n}]
c_g	tracer gas volume concentration	[-]
C_d	discharge coefficient, taking account for friction losses	[-]
D	diameter or average side of a duct	[μ]
g	acceleration of gravity, which is about 9.81	[m/s^2]
K	calibration coefficient	[-]
M	average molecular weight of the air, that is 0,02894	[kg/mole]
m	mass	[kg]
n	flow exponent (0.5 n 1)	[-]
p	pressure, sound pressure	[Pa]
Q	mass air flow rate	[kg/s]
q	Volume air flow rate	[m^3s^{-1}]
q_F	Volume air flow rate through a fan	[m^3s^{-1}]
R	gas constant (8.31696	[J/mole K]
Re	Reynolds number	[-]
S	tracer injection mass flow rate	[kg/s]
$s(x)$	estimate of a standard deviation $\sigma(x)$ of a quantity x.	
$\langle v \rangle$	average velocity of a fluid	[m^3/s]
T	absolute temperature	[K]
T_e	external air temperature,	[K]
T_i	internal air temperature,	[K]
$T(P,\nu)$	confidence interval of the Student distribution with ν degrees of freedom and a probability P.	
V	volume	[m^3]
V_f	volume of a float in a rotameter	[m^3]
v	wind speed	[m/s]
x_i	measured quantity	
y	$= y(x_1, ...x_i,...)$ quantity obtained by interpreting the measurements	
z	vertical position taken from the ground	[m]
z_0	position of the neutral plane	[m]
α	angle between the horizontal and an inclined tube	[-]
β	reduction ratio, which is the ratio of the smallest diameter to the diameter of the pipe.	[-]
Δh	liquid column height difference	[m]
Δp	pressure difference across a leakage	[Pa]
Δt	time interval	[s]
δy	error on the variable y	
μ	viscosity	[kg/(s.m)]
ν	= μ/ρ: kinematic viscosity, which is about 15 10^{-6} m^2/s for the air	[m^2/s]
ρ	density	[kg/m^3]
ω	rotation speed	[s^{-1}]

1. Introduction

The increasing requirements with respect to information on leakage data of buildings and components in these buildings have resulted in the development of a variety of measurement methods. Some of these are frequently used, especially in certain countries, while others are only applied by a few researchers. The main reasons for such a limited use are the need of sophisticated equipment, highly specialized technicians, very time consuming measurements, or a combination of these.

Measurement procedures for determining the airtightness of whole buildings or for determining the airtightness of building components in the laboratory are very well described in various publications and in a number of standards.

The development of multizone ventilation computer codes requires measured data sets for model validation. These data sets must include detailed information concerning the magnitude and distribution of leakage paths. It is realistic to expect a wider use of these computer codes in the future to assist in a design of efficiently ventilated buildings. For the evaluation of the performances of existing buildings, an approximate determination of the leakage distribution is also necessary. In addition, research on pollutant distribution in buildings (e.g. radon and water vapor) requires information on leakage paths. Moreover, information on the leakage distribution is needed in the framework of upgrading the airtightness performance of buildings.

For almost each problem there is in principle an appropriate technique available. These techniques and associated applications are summarized in Tables 3.5, 3.6 and 3.7 of Part I.

Whole building pressurization is clearly the most widely used technique and this is covered by several national and international standards describing in detail the procedure to be followed. Such a well described situation is not found for techniques aiming to quantify the inter-zonal leakage within buildings.

The required level of accuracy clearly varies from one application to another. It ranges from very detailed data in the case of model validation to an approximate estimate of the leakage distribution in the case of a global pressurization test. This means there is a need for various types of methods. It is also clear that the magnitude of the flow rates can vary over wide ranges, typically from less than 1 dm^3/s to more than 100 m^3/s.

This part of the guide is intended to help the user in selecting the appropriate measurement method for building airtightness and leakage path evaluation.

Section 2 presents an overview of the basic principles of whole building and component leakage measurements.

Pressure and air flow rate measuring instruments, which are the basic needs for air leakage determination, are described in Section 3..

Section 4 provides a comprehensive description of current pressurization techniques covering both qualitative and quantitative measurements of component leakage determination.

Section 5 addresses the treatment of measured data, while section 6 presents an overview of the available equipment.

Finally the current standards for airtightness measurements are briefly reviewed.

2. Principles of the Pressurization Techniques

This chapter examines the basic principle and practice of evaluating building envelope and building component airtightness by pressurization and related techniques.

2.1. General Principle

2.1.1. Basic Measurement Conditions and Relations

The main reason for conducting building airtightness measurements is to characterize the leakage of the building fabric in the absence of climatic or other variable parameters influencing the results. Therefore the building (or part of the building or a particular component) is pressurized or depressurized in order to create a pressure difference large enough to minimize influences from wind and temperature differences, on the results. This pressure differential is built up and maintained by means of a fan, forcing an air flow through the envelope or component to be evaluated. This amplified air flow can be put in evidence by both qualitative (visualization, ...) as well as quantitative (measurement of the air flow for a given pressure difference) techniques in order to assess the leakage locations, areas and characteristics.

The following general models can be used for the characterization of the air leakage:

The power law:

$$q = C\,\Delta p^{n} \tag{2.1}$$

and the quadratic law:

$$\Delta p = a\,q^{2} + b\,q + c \tag{2.2}$$

where:

- q is the volume air flow rate through the leakage site [m^3/s];
- Δp is the pressure difference across the leakage site [Pa];
- n is the flow exponent (0.5 n 1);
- C is the air flow coefficient [$m^3s^{-1}Pa^{-n}$], and
- a and b are coefficients representing respectively the turbulent and laminar parts of the quadratic law [Pa s/m^3 and Pa s^2/m^6].
- c is an optional constant representing the zero-flow pressure difference [Pa]. Note that including this constant ensures that the quadratic curve fit is not forced through the origin as is the case with the power curve fit.

Equations (2.1) and (2.2) can also be written in terms of mass air flow rates.

The purpose of quantitative pressurization measurements is to determine these coefficients and exponents of either of the above models describing the air flow through the envelope or component.

2.1.2. Types of Techniques

There are two basic approaches to the evaluation of building airtightness: DC pressurization and AC pressurization. The former technique has been in use for many years and currently measurements can be made in many types of building often using commercially available equipment (see Section 6.3). DC pressurization is also the subject of several national standards and guidelines (see Section 7). The second technique, AC pressurization, has been developed more recently. It has yet to be used extensively in field work but because of potential advantages it may have over DC pressurization, it too will be considered here. These general pressurization techniques are introduced in Section 2.2.

To evaluate component leakages a number of qualitative and quantitative methods are used. These are briefly described in sections 2.3 and 2.4 respectively.

More detailed descriptions of all these techniques are given in chapter 4.

2.1.3. Error Analysis

It is useful to perform a complete error analysis before (and of course also after) carrying a measurement with any of the techniques described below. Since the leakage characteristic is not

linear, surprising causes of errors can be revealed by such a study, and their knowledge allow to improve the measurement technique, and therefore confidence in the results *[Herrlin and Modera, 1988, Fürbringer and Roulet, 1991]*.

2.2. Methods for Whole Building Evaluation

2.2.1. DC Pressurization, External Fan

The majority of measurements in this category have been performed in small residential buildings. The technique usually involves replacing an external door with a panel containing a powerful, variable speed fan. A correctly designed panel will not require the existing door to be removed from its hinges. Initially developed and used as a research tool, several commercial blower doors are now available (see Section 6.3). These can be adjusted to fit snugly into any domestic door frame. Air flow through the fan creates an artificial, uniform, static pressure within the building. Internal and external pressure taps are made and a manometer is used to measure the induced pressure differential across the building envelope. It has become common practice to test buildings up to a pressure difference of 50 Pa.

Some means must also be provided to enable the volumetric flow rate through the fan to be evaluated. The aim of this type of measurement is to relate the pressure differential across the envelope to the air flow rate required to produce it. In general the higher the flow rate required to produce a given pressure difference, the less airtight the building.

The air flow required to produce a given pressure difference under pressurization (air flow in) will not necessarily be identical to the flow required to produce the same pressure differential under depressurization (air flow out). This difference is due, in the main, to the fact that certain building elements can act as flap valves. For example, some types of window will be forced into their frames under pressurization while the reverse will be true for evacuation. This implies that the actual leakage area of the building envelope will be a function of the type of test conducted. *[Baker, Sharples, and Ward, 1986]* suggest that, in addition to this effect, the asymmetric geometry of some cracks with respect to the flow direction may explain significant changes in leakage characteristics with no associated change in leakage area. This type of crack may occur around casement windows where one leg of an L-shaped crack may be longer than the other. Hence, ideally, the fan and flow measuring mechanism must be reversible.

The general configuration for a pressurization/depressurization test is shown in Figure 2.1. The measurement procedure will depend upon the purpose of the test and the exact equipment used.

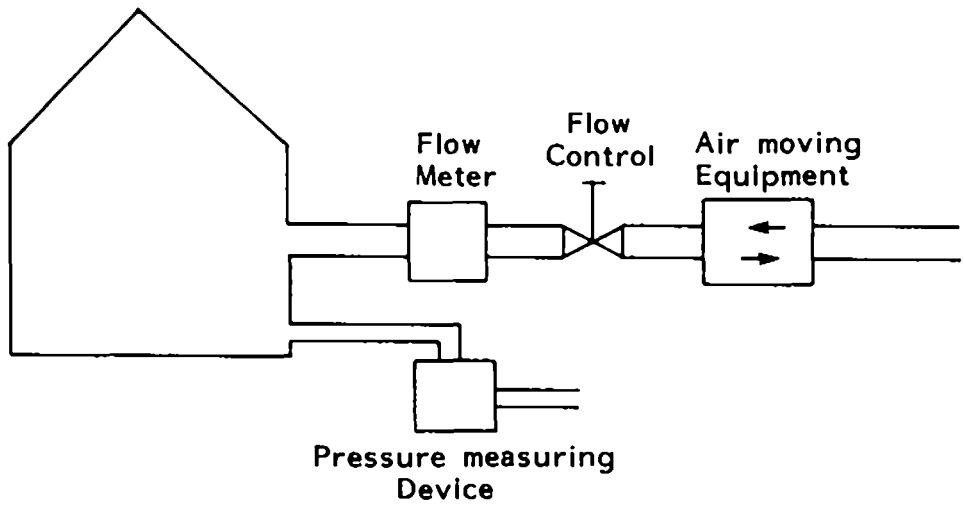


Figure 2.1: Schematic of whole building airtightness test (after [ISO 9972, 1991])

Theoretically there is no limit to the size of building which can be examined with DC pressurization. However, the maximum volume of enclosure which may be pressurized is governed by the overall

airtightness of the structure and the size of the available fan. Even if large fans are available, in large leaky structures it may be possible to only achieve a limited range of pressure differentials. Several researchers have used trailer mounted fans with maximum flow capacities of about 25 m^3/s to examine buildings with volumes in the region of 50 000 m^3 (see, for example, *[Shaw, 1981]*).

2.2.2. DC Pressurization, Internal Fan

Because of the size and cost of trailer mounted equipment and the inherent difficulties of transportation and required manpower, other techniques have been developed for the examination of large buildings. One method is to create the required pressure differential using the building's existing air handling system (see Figure 2.2). This technique relies on the building possessing a suitable mechanical ventilation system which can be adjusted to meet the needs of the measurement. Essentially, the supply fans are operated while all return and extract fans are turned off. All return dampers must be closed so that the air supplied to the building can only leave through the leakage sites. Further details of this type of technique are provided in Section 4.1.2.

The analysis of measurements results proceeds along the same lines as that for small buildings, but because of the large building volume it may not be possible to achieve a pressure difference of 50 Pa. Persily and Grot *[1986]*, for example, compared the results of several building measurements by quoting the volume flow rate at a pressure difference of 25 Pa.

DC pressurization is subject to the disturbing influence of natural pressure fluctuations created by the wind. Hence most measurements in a DC pressurization test are made at pressure differentials far above those created by natural forces. This may lead to inaccuracy if the results are extrapolated to lower pressure differentials.

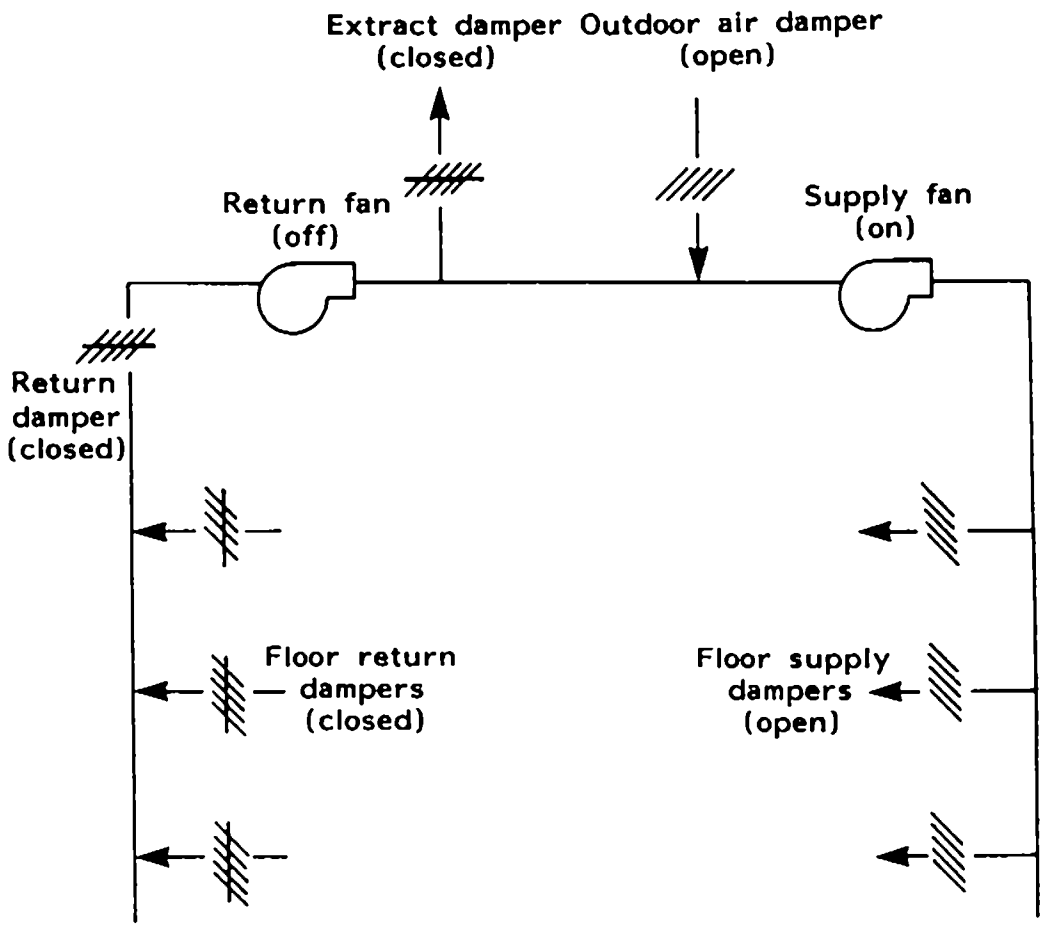


Figure 2.2: *Schematic of DC pressurization using internal fans [Persily and Grot, 1986]. State of fans and dampers during pressurization test conditions are shown between brackets.*

2.2.3. AC Pressurization

AC pressurization is a technique which allows building airtightness to be examined at similar pressure differentials with minimal interference from climatic forces. In this technique a small varying pressure difference is created across the building envelope, which is distinguishable from naturally occurring pressure fluctuations. Because of this, air flow through the envelope, induced by the applied pressure differential, can be evaluated *[Modera and Sherman, 1985]*.

In practice a piston is used to create a continuous harmonic change in the internal volume of the building under test. This creates a time-varying pressure difference across the envelope. The airtightness of the building affects the amplitude and phase of the pressure change due to the harmonic volume change.

By measuring the amplitude of the pressure response inside the building and the phase relationship between this pressure and the velocity of the piston, the air flow through the envelope can be evaluated. The effects of air leakage sites are evident using this method, however large openings (such as open windows, which should anyway be closed during the test) can go undetected.

2.2.4. Pulse pressurization

Methods avoiding the installation of heavy instruments could be useful, even if they are not very accurate. Such a method is even patented *[Yuil, 1985]* but was not widely diffused.

Based upon the theory of pressure evolution in a leaky cavity, a decay technique that could be used to quantify the leakage was developed and tested *[Sherman and Modera, 1988]*. The pressure is suddenly enhanced in the measured volume, e.g. by slamming the entrance door. The leakage characteristics are identified by fitting the measured pressure decay on theoretical values.

2.3. Methods for Qualitative Evaluation of Component Leakages, Leak Visualization

There are a number of measurement techniques which provide qualitative information about air infiltration and ventilation. Several of these methods are designed to provide information about the sources of air leakage in buildings. The most sophisticated of these methods is infrared imaging or thermography. In this technique thermal radiation, which depends on the surface temperature, is converted by the infrared radiation sensing system (thermographic camera) to a visible thermal image. In order to detect leakage defects, the building is usually depressurized using a DC technique. This infrared method works best when there is a distinct temperature difference between the inside and outside of the building. The ingress of cold external air then cools the surfaces adjacent to the cracks. These cold areas are revealed on the thermal image and hence leaks can be located. It is also possible to detect air leakage from the living space to the roof space by pressurizing the building and observing the flow of warm air into the attic. A full account of the use of the application of thermography to air infiltration and airtightness measurements is given by *[Pettersson and Axen, 1980]*.

Thermal imaging equipment is expensive and requires a high level of expertise for effective operation. The main difficulty lies in being able to separate air leakage paths from other thermal anomalies in the envelope such as thermal bridges. Smoke visualizations offer a cheaper and easier alternative for leak detection. Smoke can be produced in several ways, the most convenient often being a hand-held puffer and smoke stick. This technique simply involves pressurizing a building and using a smoke source to trace the paths followed by the leaking air. Smoke can also be used for flow Visualization through larger openings such as internal doors.

Sound waves pass readily through many of the same openings in the building envelope that allow air leakage. Acoustic detection of leakage paths is therefore possible. A steady or wobbling high-pitched sound source is placed within the building and leaks are "listened for" on the external surface. A small microphone or stethoscope is used and leaks correspond to an increase in the intensity of transmitted sound *[Sonoda and Petersen, 1986]*.

2.4. Quantitative Determination of Building Component Airtightness

The most accurate way for determining component leakage is testing the component in the laboratory. This is a standardized procedure for windows and doors in many countries. This procedure is not at all appropriate for testing walls or roof components in real buildings, therefore other techniques to be used on site have been developed.

A brief overview of the methods is given in this subsection while more detailed information is given in Section 4.3.

The leakage characteristics of individual external buildings components can be evaluated from site measurements. In its simplest form this consists of sealing a chamber over the interior face of the building component (see Figure 2.3.). Air is supplied to or extracted from the chamber at a rate required to maintain a specified static pressure difference across the specimen. The resultant air flow through the specimen and the specified pressure difference are recorded.

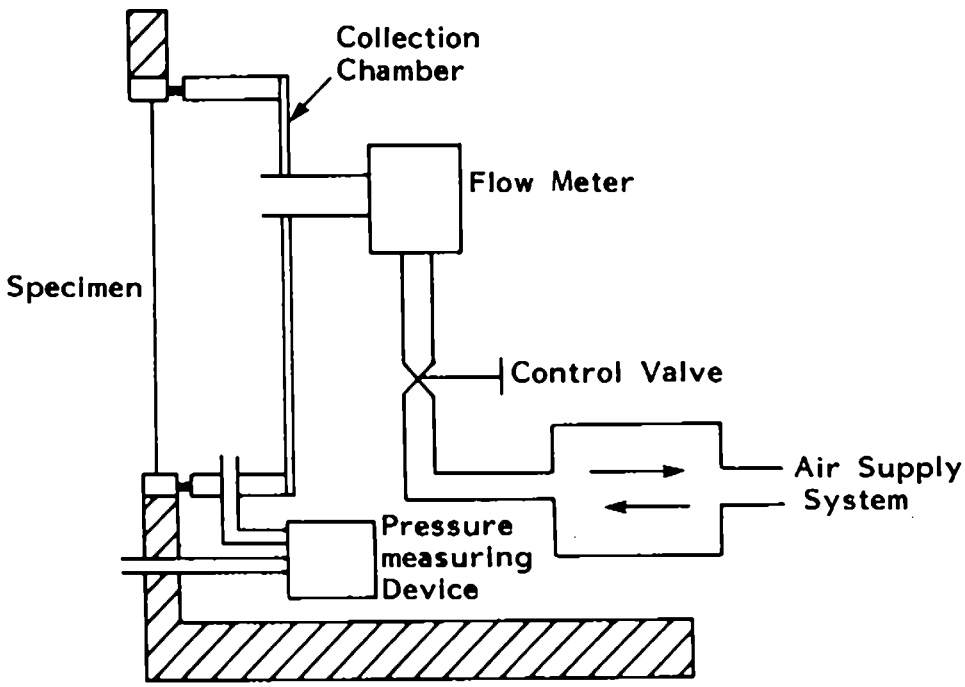


Figure 2.3.: Schematic of component airtightness test using collector chamber (after [ISO 9972, 1991])

This test is made more accurate if the pressure in the room containing the component is balanced to that in the collection chamber. This pressure balancing can be performed by using a secondary or auxiliary fan located in the room envelope. An example of this method is illustrated in Figure 2.4., where fan 'a' is used to depressurize the room to a given pressure differential and fan 'b' is adjusted to maintain a zero pressure difference between the collection chamber and the room. The leakage flow through the target area is then measured at Q. The increase in accuracy is due to the elimination of unwanted leakage between the collecting chamber and the rest of the room. More details are given in 4.3.1.

Whole house fan pressurization may also be used for evaluating the leakage path distribution by selectively sealing different potential leakage paths (using , for example, plastic sheeting or sticky tape) and measuring the resulting changes in air flow rate. The fraction of the total air leaking through the sealed components of the building envelope can then be deduced. Further components may be sealed and pressurization repeated, hence this technique is often known as reductive sealing. As the components will be generally sealed from the inside, it is preferable that an over-pressure rather than an under-pressure be created within the building. Pressurization will tend to force the seal onto the component while a negative pressure will tend to act against the seal making it less airtight.

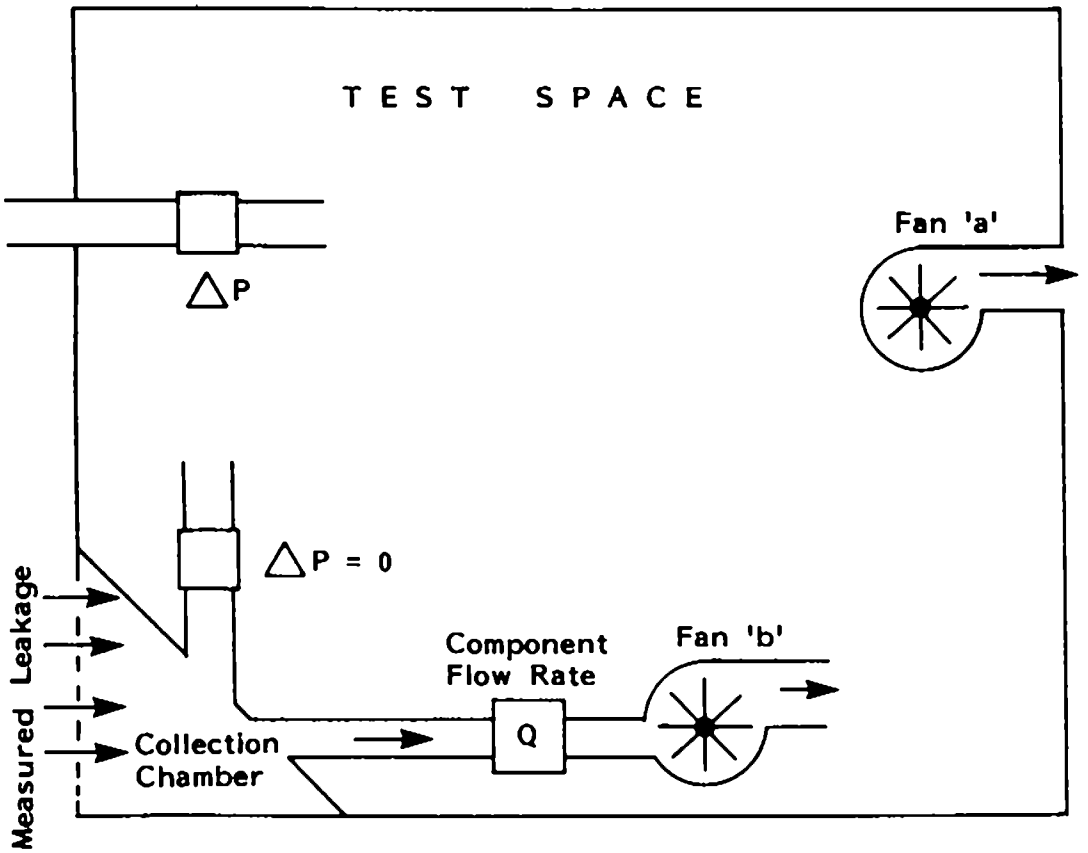


Figure 2.4.: Use of secondary fan to increase accuracy of building component airtightness test (after [Baker and Valentine, 1987])

Site measurements of component leakage can also be made by using a pressure compensating flow rate meter (e.g. *[Phaff, 1987]*). This device operates on the zero pressure principle whereby the resistance of the measuring instrument is compensated by means of an integral fan. This type of equipment was originally developed for measuring the flow rate at the supply and exhaust grilles of mechanical ventilation systems. When correctly adjusted the presence of the device does not influence the air flow and therefore the flow rate can be determined directly.

For this particular application a collection chamber is placed over the area where the cracks are situated and the flow meter is placed over an opening in the box. By compensating the pressure difference the air flow through the cracks is evaluated.

The collection chamber does not need to be airtight, since at nearly zero pressure differential, unwanted leak flows will be minimal.

This type of device can also be used to assess leakage distribution during pressurization tests (see Figure 2.5.).

The building is pressurized in the normal way (see Section 2.2.) and a shield of hardboard is placed in the opening of an internal door. The flow meter is placed over an opening in the shield and at pressure compensation the air flow through the room facade is indicated. Bypass flows through adjacent internal walls will be minimal near pressure compensation. However large internal leaks may make it impossible to see when compensation is reached.

Building component airtightness measurements can be performed under controlled laboratory conditions. A test chamber is used, into which various test specimens are fitted. The air flow through and the pressure difference across the test specimen can be accurately determined under laboratory conditions. This type of test enables large numbers of specimens to be examined under similar conditions. The results of such tests are often reported in terms of leakage per unit area or leakage per unit crack length. It must be noted that laboratory based measurements may produce significantly different results to site evaluations of seemingly identical components. This is mainly due to the fact that laboratory workmanship may be under closer control than that on site.

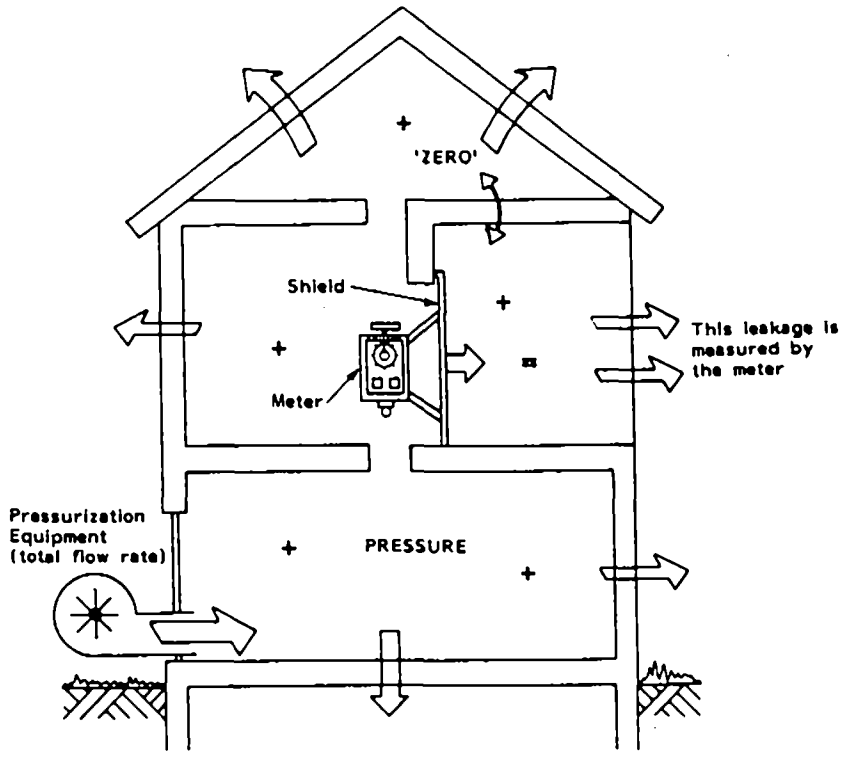


Figure 2.5.: Pressure compensating flow meter being used during pressurization test (after [Phaff, 1987])

The air leakage through the whole surface of individual external or internal walls can be evaluated using a technique known as balanced fan pressurization. This method is particularly appropriate for large multi-cell buildings such as apartment blocks or multi-family dwellings. For example consider one apartment in a multi apartment building. The apartment will have a single external wall with up to five other walls being shared with adjoining corridors or apartments. If a normal fan pressurization test such as that described in Section 2.2. is performed, the measured leakage will include the leakage to several internal zones.

If however the pressure in these other zones is balanced with that in the main test zone, i.e. zero pressure difference across internal walls, then no air leakage will occur through internal flow paths and only the leakage to the external environment will be evaluated.

In order to achieve this pressure balance each surrounding zone must be pressurized along with the main measurement zone. Thus more than one set of fan pressurization equipment is required for this type of test. Also control procedures are needed in order to maintain zero pressure differences where required (see Section 4.3.3).

The technique is not limited to multi-compartment buildings but it may also be used in a variety of other situations. For example, in a row of terraced houses, one house is pressurized in the normal manner whilst the adjacent houses are balanced to the same pressure. This enables the leakage through the external walls of the dwelling to be separated from the leakage through the partition walls.

3. Pressure and Air Flow Measurements

This chapter presents the principles of various instruments used to measure air flow rates and pressure differentials. These parameters are used to determine the leakage characteristics of buildings or building elements. Additional methods especially dedicated to flow measurements in ducts are described in Part V.

3.1. Differential Pressure Equipment

Sensitive differential manometers are necessary to assess the variation of air leakage with pressure. The required pressure range is 0 to 70 Pa, with a minimum accuracy of 1 Pa.

Two basic principles are used for such low pressure measurements. These are: a) liquid column manometers, (a U-tube filled with a light liquid, generally water) and b) membrane manometers, (measuring the bending of a membrane). The properties of such instruments, , are summarized in table 3.1 and described in further detail below.

Instrument type	Range [Pa]	Indicated Accuracy [Pa]	Comments
U-tube	0 to 10^5	10	Simple but not sensitive
Inclined tube	0 to 2500	1	Must be levelled
Micromanometer	-10 to 3000	1	Not readily portable
Membrane, mechanical	Any	*1 to 10 %*	Not very sensitive
Membrane, electronic	0 to 20	0.1	Requires power but provides a
	0 to 200	1	a recorder output

***Table 3.1.**: Properties of some pressure measuring devices.*

3.1.1. Liquid Column Manometer

These manometers are U-tubes filled with a liquid of density ρ. If a pressure difference, Δp, is applied between both tubes, the difference in liquid column height, Δh, is:

$$\Delta h = \rho\, g\, \Delta p \tag{3.1}$$

where g is the acceleration of gravity, about 9.81 [m/s^2].

With water, a differential pressure of 1 Pa gives a variation in height of 0.1 mm, which is too small for the precision required. Two ways are used to enhance the sensitivity which are draft gauges and micromanometers.

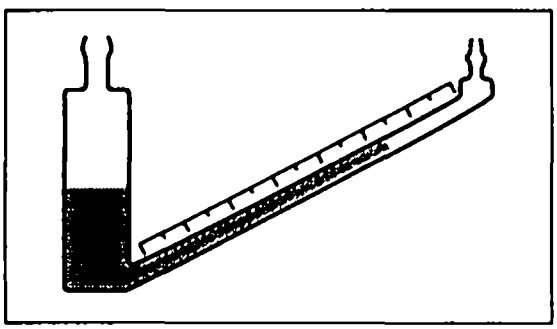


***Figure 3.1.**: Inclined manometer*

Draft gauges or inclined manometers are U-gauges set to an angle (Figure 3.1). In such instruments, only one branch of the tube is inclined and the other is a reservoir. The sensitivity is enhanced by 1/sin α, where α is the angle between the horizontal and the inclined tube. Then:

$$\Delta h = \frac{\rho\, g\, \Delta p}{\sin \alpha} \qquad (3.2)$$

It is recommended that 1/sin α be not larger than 10, that is $\alpha \geq 5.74°$. Since the sensitivity depends on α, the instrument must be carefully levelled before use.

Micromanometers are U-tube manometers where the level of the liquid is observed with an amplifying optical system. One system is a finely engraved glass rule fixed on a floater following the liquid level. The level is read on the glass rule either with a microscope or with an optical projection system.

3.1.2. Membrane Manometers (Mechanical, Capacitive, Inductive)

A pressure difference applied to both sides of a membrane bends it towards the low-pressure side. Several systems are used to measure the bending, these are a) mechanical, b) capacitive or c) inductive systems (fig. 3.2).

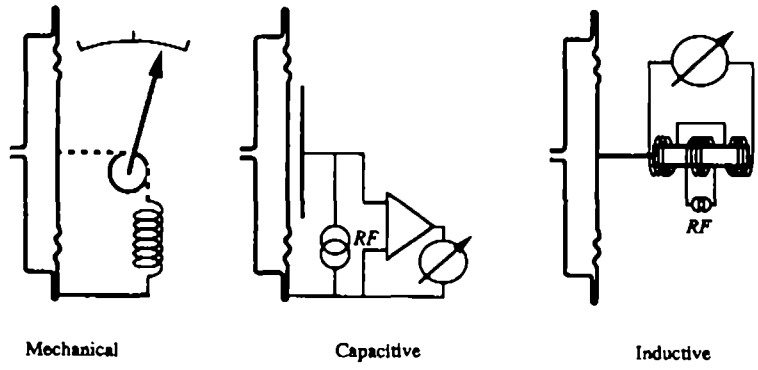


Figure 3.2: Schematic representation of various systems for membrane manometers.

The mechanical system uses a pulley and a lever to act on the indicating needle.

Electrical transducers are used in modern and sensitive instruments. In the capacitive system, the surface of the membrane is one plate of a variable capacitor, the capacitance of which varies according the distance between that membrane and a reference, fixed plate.

In the inductive system, the membrane moves an iron core between three coils acting as a transformer. This core couples the primary, central coil either to the left or the right coil. If an alternating current is brought to the central coil, the voltage drop through the external coils is a measure of the position of the membrane.

3.2. Air Flow Rate Measurement Equipment

Many methods are used to measure air or tracer gas flow rates with each having its advantages and disadvantages. It is therefore necessary to select the most appropriate according to the application. The available instruments and their properties are summarized in table 3.2.

Instrument type	Range [m^3/s]	Attainable Accuracy	Application
Micro-orifice	10^{-6} to 10^{-3}		For gases under pressure
Balance	10^{-14} to 10^{-2}	0.01%	For gases in containers
Gasometer or volume displacement	Any	0.5%	Calibration
Soap bubble flow-meter	10^{-8} to 10^{-6}	2%	Very low flow rates
Variable area flow meter	10^{-6} to 10^{-2}	2%	Low flow rates
Sharp Edge Orifice	Re > 5000	1%	Flows in pipes
Nozzle	Re > 5000	1%	Flows in pipes
Venturi	Re > 5000	1%	id., low pressure drop
Tracer Gas	Any	5%	Field measurements

Table 3.2.: Characteristic of flow rates measurement methods. Re is the Reynolds number.

3.2.1. Micro-Orifice Method

This method is based on measuring the pressure drop across a small orifice opening of diameter between 10 μm and 1 mm. The micro-orifice technique is mainly used for precise injection of minute quantities of tracer gas but may also be used for the determination of residual leakage through very airtight or very small enclosures. It is suitable for flow rates between less than 1 ml/s and approximately 0.1 l/s and has long term stability. Leakage measurement are made by imposing a fixed air flow rate and measuring the resulting pressure differential across the element under test.

If the pressure difference across the orifice is sufficiently high (e.g. for air or N_2O more than ca. 2.10^5 Pa) then the gas flow is supersonic and a linear relation exists between the pressure difference and the mass flow rate through the orifice.

An example of a tracer gas dosing valve is showed in Figure 3.3. One of the disadvantages of the method is the limited variation in flow rate which can be realized by one orifice.

A similar technique having the same performances is the mass flow controller (see Section 5.2.1).

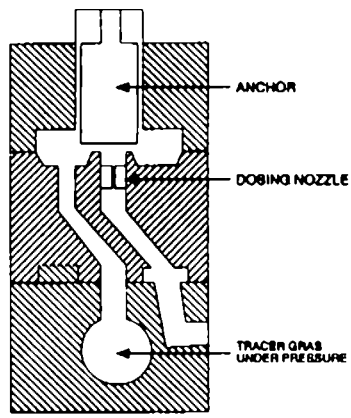


Figure 3.3.: Tracer gas injection valve

3.2.2. Balance Method

The change in weight over time of a gas cylinder releasing gas, in combination with the known density of the gas, allows the flow rate from the cylinder to be determined. Usual gas cylinder are used and placed on an electronic balance. The gas flow rate is controlled by the pressure relief valve. The use of the balance method is suitable for the determination of the airtightness of very airtight and/or very small enclosures if more classical methods using a fan are not possible.

The volume air flow rate, q_v, is calculated as:

$$q_v = \frac{m(t) - m(t+\Delta t)}{\rho\, \Delta t} \qquad [m^3/s] \qquad (3.3)$$

where:

$m(t)$ is the mass indicated on the balance at time t [kg]

ρ is the density of the gas [kg/m^3]

Δt is the time interval [s]

The expansion of the gas at especially high flow rates cools the gas and sometimes creates freezing problems. This can be avoided by turning the bottle upside down.

Figure 3.4 shows the set-up while table 3.3 gives the properties of some gases.

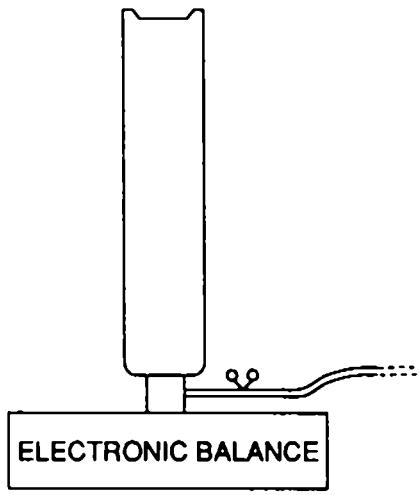


Figure 3.4.: Gas bottle on an electronic balance

3.2.3. Gasometer and Volume Displacement

The gasometer is used for calibration purposes. Basically, it is a graduated container floating upside down on a liquid. The gas is introduced into the container which rises in proportion to the quantity of the gas injected (fig. 3.5).

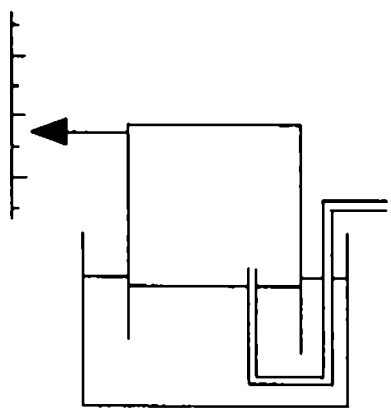


Figure 3.5.: Principle of a gasometer.

The flow rate is deduced from the time needed to full a given volume in the container. The accuracy depends on the volume of the container (which itself limits the measurable flow rate) but may be as good as 0.5 % provided a constant temperature is maintained.

The rotating cylinder gas flow meter (fig. 3.6) is suitable for gas flows from 10^{-7} to 10^{-3} m^3/s. The gas flowing into this flow meter fills the chambers contained in a cylinder fixed to the axis. The bottom of the cylinder is submerged into a liquid, and the incoming gas makes the axis rotate at an angle proportional to the volume of gas. A needle fixed to the cylinder and a counter indicates the volume of gas which has passed through the instrument.

To get accurate measurements, the level of instrument, and the liquid within it shall be exactly adjusted and the instrument shall be horizontal. The pressure and temperature in the circuit must also be accurately controlled and known. From these indications the mass flow can be deduced.

Special care should be taken if the measured gas is soluble in the liquid of the flow meter. In this case, the solution must be saturated and time is required to reach an equilibrium after each change in temperature or pressure.

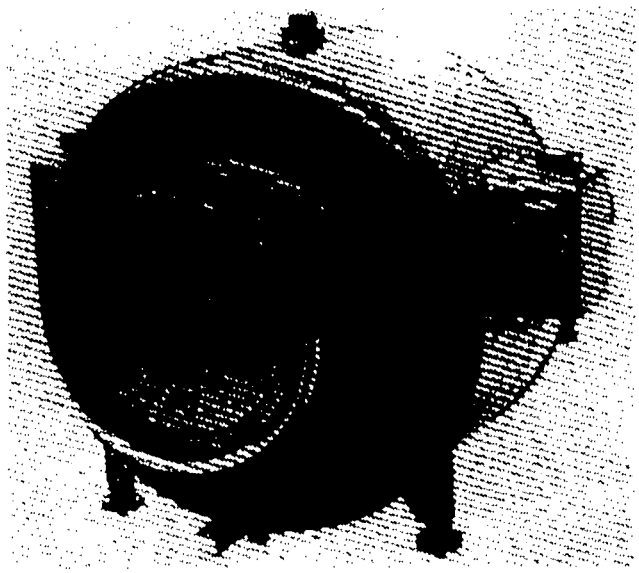


Figure 3.6: Rotating gas flow meter [Compagnie des Compteurs, 1975]

3.2.4. Soap Bubble Flow Meter

This very simple and portable instrument can be used in the field for the measurement of very low flow rates. The gas is passed into a U- tube, in the bottom of which a soap solution fills a rubber bottle (fig. 3.7). Pressing that bottle makes the gas bubble through the soap solution with result that one or more soap films are traveling through the graduated tube. The travel time between the start mark and the mark corresponding to a suitable volume is measured with a chronograph and the flow rate is deduced from the ratio of the measured volume to the time interval.

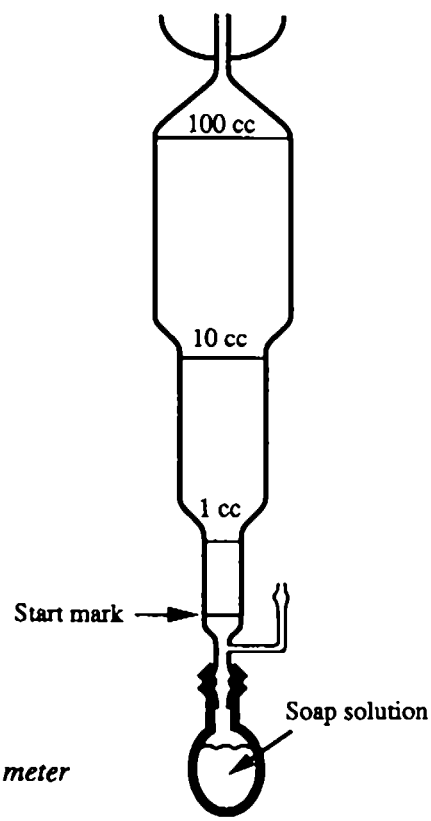


Figure 3.7: Soap bubble flow meter

3.2.5. Variable Area Flow Meter (Rotameters)

The rotameter consists of a float that is free to move vertically in a transparent tapered tube (fig. 3.8). The metered fluid enters at the narrow bottom end of the tube and moves upwards passing through the annular space between the float and the walls of the tube. Since the area of that annular space grows with the height, the float finds an equilibrium position at which its weight is compensated by the thrust of the fluid.

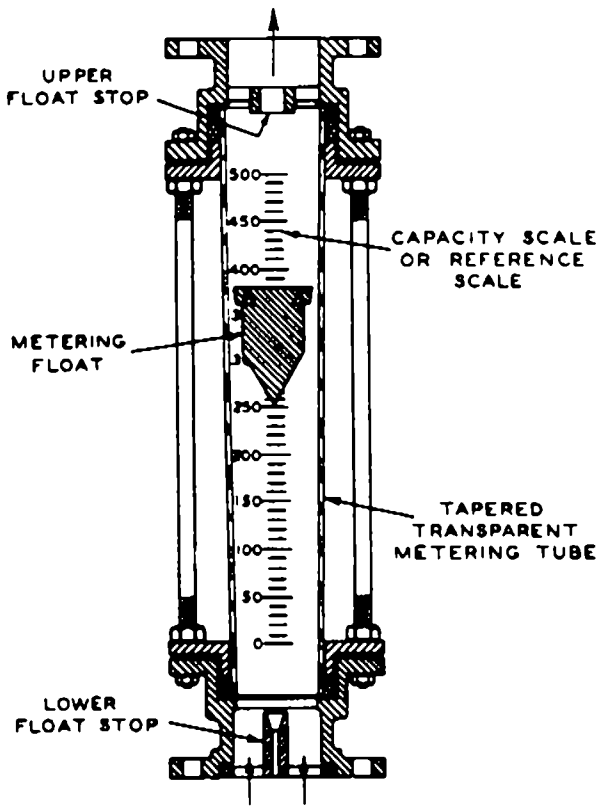


Figure 3.8: Cut through a variable area flow meter [ASHRAE, 1989].

The mass flow, Q, is given by:

$$Q = K A \sqrt{\frac{2 g \rho V_f (\rho_f - \rho)}{A_f}} \tag{3.4}$$

and is nearly proportional to the area of the annular space, A *[ASHRAE, 1989]*.

In this equation, g is the acceleration of gravity, ρ_f and ρ are respectively the density of the float and of the measured fluid, V_f is the volume and A_f the cross section of the float. The calibration coefficient, K, should be determined for each instrument and for each measured fluid. K may depend on the Reynolds number, and hence on the flow rate.

It is remembered that the Reynolds number is defined as

$$Re = \frac{\langle v \rangle D}{\nu} \tag{3.5}$$

where $\langle v \rangle$ is the average velocity, D is the diameter (or the average size) of the duct and ν the kinematic viscosity, which is about 15 10^{-6} m^2/s for the air.

This instrument is reliable, accurate and relatively cheap if the diameter of the tube is less than 0.1 m.

3.2.6. Orifice, Nozzle and Venturi Flowmeters

The change in pressure in a pipe with a section of restricted area can be calculated by the Bernoulli law, provided there is neither friction nor compression. A relationship can hence be found between a pressure difference along the flow line and the corresponding flow rate, which may itself be deduced from a differential pressure measurement.

However, since there is a slight friction, the mass flow is:

$$Q = C A \sqrt{\frac{2 \Delta p}{1 - \beta^4}} \tag{3.6}$$

where:

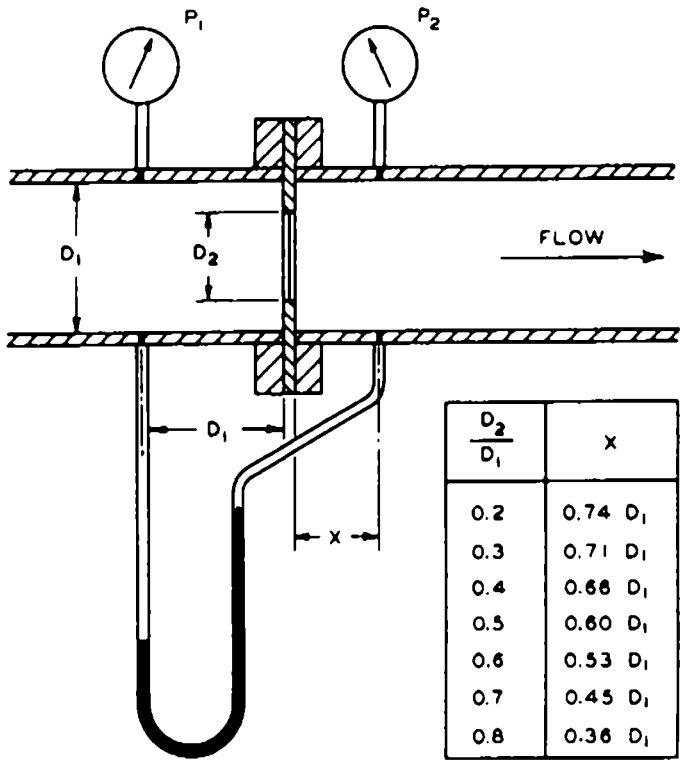
C is the discharge coefficient, taking account for friction losses,

A is the smallest cross section in the flow

Δp is the pressure difference between two taps properly located,

β is the reduction ratio, which is the ratio of the smallest diameter to the diameter of the pipe.

The flow may be restricted with an orifice plate (fig. 3.9), a nozzle (fig. 3.10) or a Venturi tube (fig. 3.11).



$\frac{D_2}{D_1}$	X
0.2	0.74 D_1
0.3	0.71 D_1
0.4	0.68 D_1
0.5	0.60 D_1
0.6	0.53 D_1
0.7	0.45 D_1
0.8	0.36 D_1

Figure 3.9: Orifice plate and location of the pressure taps [ASHRAE, 1989]

The most sophisticated and expensive is the Venturi tube in which the discharge coefficient is nearly 1 and constant for $Re > 2 \times 10^5$ and higher than 0.94 if $Re > 50\,000$. Moreover, this device does not induce large pressure drop in the flow.

At the other end of the spectrum is the simple and cheap orifice plate, which induces a large pressure drop and shows discharge coefficients which may be as low as 0.6, depending on the Reynolds number. The characteristics of the nozzle lie in between.

It follows that, even if discharge coefficients are found in the literature (e.g. *[ASHRAE, 1989]*), it is recommended to calibrate the orifices and the nozzles for the full flow range and for each pressure tap

location used. The Venturi needs a calibration only for high accuracy measurements or for low Reynolds numbers.

All these flow meters shall be mounted between two straight pipes, the upstream pipe being up to 30 pipe diameters long, depending on the type of perturbation upstream, and the downstream part at least 3 diameters long. If a straightening vane 2 diameters long is installed upstream, the distance between this vane and the flow meter may be reduced down to 10 diameters.

Here again, the device which is most sensitive to perturbation is the orifice, then the nozzle. The Venturi tube is the less sensitive.

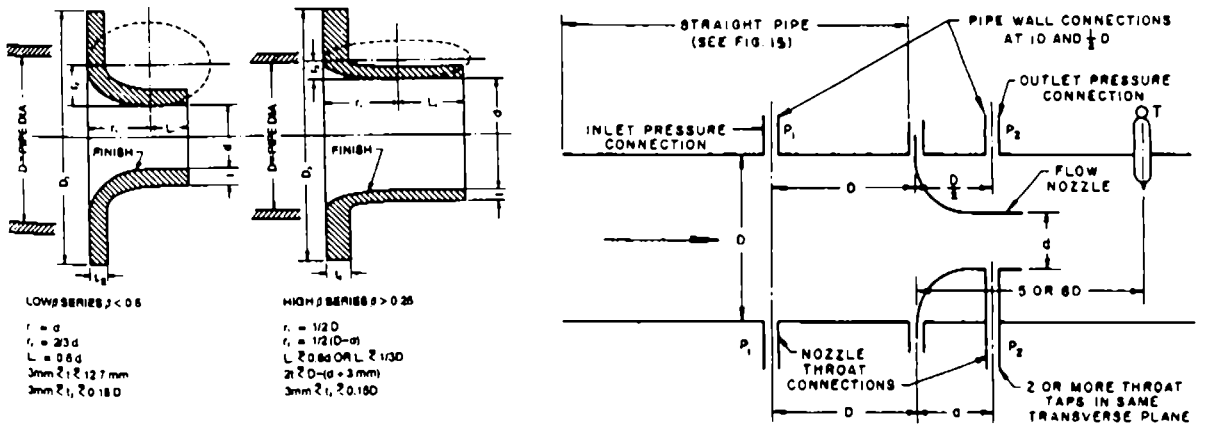


Figure 3.10: Nozzles and location of the pressure taps [ASHRAE, 1989]

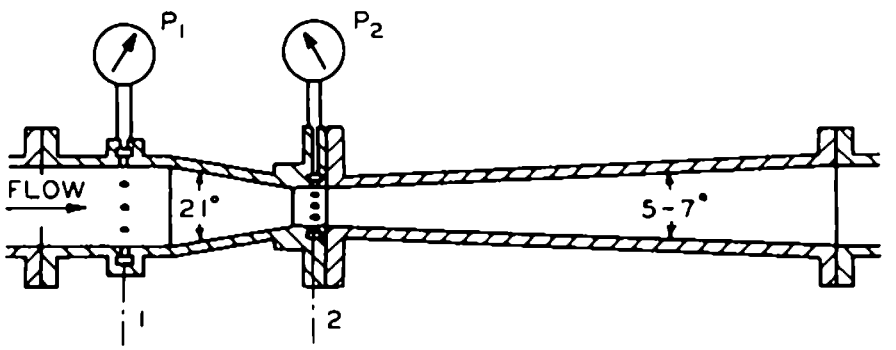


Figure 3.11: Venturi tube [ASHRAE, 1989]

3.2.7. Tracer Gas

To measure the air flows with tracer gases, a known quantity of tracer is injected in a section of the flow to be measured. Its concentration is measured downstream at a location where the tracer is well mixed with the air.

If the tracer is injected at a constant flow rate, S, and when a steady state is reached, the mass air flow rate, Q, is:

$$Q = \frac{m}{\int (C_g(t) - C_{gO})\, dt} \tag{3.8}$$

where the integral is taken during all the time when $C_g(t) - C_{gO} \neq 0$.

This method can be used in ducts with significant flow perturbations and in rooms, at grilles etc. Its accuracy depends not only on the accuracy of the injection and of the analyzer, but also on the quality of the mixing. It is therefore possible but difficult to get a precision better than 5 %. This accuracy is however good enough for most field measurements.

4. Current techniques

4.1. Envelope leakage

4.1.1. DC Pressurization, External Fan

Aim of the method: This technique is used to evaluate various aspects of the air leakage of the building envelope at induced pressure differences.

Principle: A fan mounted in a duct which pierces the building envelope is used to create either excess over-pressure or excess under-pressure inside the building. This causes air to leave or enter the building via the cracks and interstices in the building envelope. The volume flow of air entering or leaving in such a manner is equivalent to that displaced by the fan. By measuring the flow rate required to create a range of pressure differentials the air leakage characteristics of the building envelope can be determined.

Range of application: This technique has been applied mainly in dwellings often using commercially available equipment (See Section 6.3. for a full account of this type of equipment). Larger buildings can be examined, providing a fan system which can displace an appropriate volume of air is available.

This technique is designed to evaluate the air leakage characteristics of a building away from the natural influences of the climate. Therefore it is preferable to conduct the measurements when the wind speed and indoor/outdoor temperature difference are at a minimum *[ISO 9972, 1991]*. Otherwise these climatic parameters may introduce unnecessary errors into the results. In extreme cases they may make it impossible to take stable readings of the flow rate and pressure differential.

The equipment and instrumentation can be divided into four basic components. These components are discussed below:

The ***variable flow rate fan*** causes air to flow into (pressurization) or out of (depressurization) the building under test. It must be possible to create a range of flow rates through the fan thus enabling a variety of pressure differentials to be created across the building envelope. If large buildings are to be tested it may be necessary to use several fans in unison.

A ***door panel*** enables the fan to be held in place in an existing aperture in the building envelope. In most practical cases the aperture used is a door frame. Essentially two types of panel exist. One made from solid panels, the other made from a flexible sheet (see Section 6.3. for more information about this subject). The main prerequisite for any panel system is that it must be able to fill and seal off the aperture into which it is placed and at the same time holding the fan firmly in position. Blower doors are door panels with a fan, calibrated in such a way that the air flow rate is deduced by the fan speed and pressure differential.

A ***flow measuring*** instrument. For this measurement method it is essential that two parameters be accurately evaluated, the first being the flow rate through the fan duct. Several techniques can be used to make this measurement. These are discussed in more detail in 2.3 and the importance of accuracy for the measurement of this parameter is examined in Section 5.

Setting up and operating details: Several countries have standards relating to this type of measurement *[Colthorpe, 1990]*, and these are examined in Section 7. There are several commercially available "blower doors" on the market and these each come with their own set of introductions (see Section 6.2.). Manufacturers directions should be followed carefully and completely when conducting a test. Several general points are discussed below.

The building should be first configured to meet the needs of the current measurement. In practice this means setting windows, vents and other apertures to the position desired by the measurement. As the aim of the technique is to produce a uniform pressure difference across all parts of the envelope, internal doors are generally left open. If the results are required in terms of air change rate, then the internal volume of the building must be evaluated. Several country standards give guidance as to how this volume should be evaluated and in general it can be calculated either from site measurements, using a tape measure, or from scale drawings using a ruler and conversion factor.

Once these preliminary setting up details have been performed, the door panel and fan can be fitted into the door frame. Care must then be taken to ensure that the panel system is secure and well sealed. Internal and external pressure tapes must be made and in several commercial blower doors an external pressure tap is located in the door panel itself. A more sophisticated approach involves leading tubes to all four external faces of a building and bringing them back to a small airtight vessel. One tube leads off from the vessel to the pressure differential instrument. The vessel essentially averages the

pressures at the four faces of the envelope. This is particularly useful when the building is completely detached and the test is being conducted under variable wind conditions.

Another important decision to make is whether to pressurize or depressurize the building. Some standards demand that both modes be performed and average results taken. The fan must then be set up to the required flow direction to be produced. The choice of location for instrumentation such as the flow rate meter and pressure differential measurement device is, in many ways arbitrary, though in cold climates the desirability of placing the equipment on the inside of the structure is obvious.

A pressurization of the building is almost always possible without any difficulties. However, leakage determination by using smoke tests, IR-detection is not so easy. A depressurization is more convenient for leakage determination since the air often enters the building. Open fireplaces are often very dirty and sometimes create serious dust problems inside the occupied space. Therefore a pressurization measurement might be the only possible technique in such cases. One should also avoid the functioning of open heating systems (fuel, oil, gas, coal,..) during a depressurization since all combustion products will come into the occupied space.

Taking the readings: Once the equipment is installed it is usual to take several pairs of readings of air flow rate and pressure differential. A range of pressure differentials should be examined, and several standards quote the pressure range to be used. A useful rule of thumb guide is to examine pressures in the range 10-60 Pa if this is achievable (see also *[ISO 9972, 1991]*). The readings can be registered by hand or, as is quite often the case in commercial blower doors, recorded automatically by some device such as microcomputer. If both pressurization and depressurization are required, then the fan flow must be reversed and the above mentioned process repeated.

Measurement duration: In small domestic buildings using a commercial blower door the measurements, including the preparation and installation, may take as little as one hour to complete. In larger buildings where more equipment and preparation is required the measurement process may take longer.

Presentation of results: A procedure as given in the ISO-standard *[ISO 9972, 1991]* is appropriate. See also Section 5.4.

Measurement accuracy: Two parameters are evaluated in this technique: air flow rate and pressure difference. If the results are expressed in terms of the air change rate, then the volume of the building must be evaluated. If other expressions of the results are made, then parameters such as the building envelope area must be evaluated.

An examination of the standards relating to the performance of this type of technique indicate that the following accuracy is desirable:

Flow Rate	± 5 %
Pressure Difference	± 2 Pa

The measurement of building volume should also be performed with care, and although no standards of accuracies exist, it should be possible to evaluate the internal volume of a test space to within 5 %, especially if detailed architectural drawings are available.

One of the most important factors with regard to the accuracy of this measurement technique is wind velocity and indoor-outdoor temperature difference. These effects generate natural pressure differences across the building envelope, which affect the measurement results by superimposing themselves on the pressure differences generated by the fan. Moreover, the wind induces turbulence, which gives rise to randomly variable pressure differentials. The higher the wind velocity and lower the induced pressure, the greater the potential inaccuracy. It is therefore advisable to conduct pressurization tests at low wind speeds. Several standards give maximum wind speeds and temperature differences at which valid measurements can be made (see section 7 and table 7.2). If the outdoor pressure is averaged over the four walls and if the pressure and flow signals are time averaged, unbiased leakage area measurements can be obtained with a scatter smaller than 11 % using fan pressurization technique, as far as the wind speed is lower than 5 m/s *[Modera and Wilson, 1990]*.

When pressurization tests are performed, cold outside air is often blown into the building and warm internal air is discharged through the leaks. It is the flow of the cold outdoor air which is measured during the test. Volume flow rates must be corrected to give a value for the rate of air flow through the leaks in the building envelope These corrections are given in Section 5.2. If the mass flow rates are measured, no correction is needed.

A full discussion on fan pressurization measurement errors, calibration procedures and correction factors is presented in *[Kronvall, 1980]*.

4.1.2. DC Pressurization, Internal Fan

This technique is used to evaluate various aspects of the air leakage of the building envelope at induced pressure differentials.

Principle of the method: The measurement principle for the DC pressurization-interval fan technique is very similar to the external fan pressurization method described in Section 4.1.1. The only major difference being that instead of an external fan the building's air-handling system is used to produce a pressure differential across the envelope. This causes air to leave or enter the building via the cracks and interstices in the building envelope. The volume flow of air entering or leaving in this manner is equivalent to the total flow through the air-handling system. By measuring the flow required to create a range of pressure differentials the air leakage characteristics of the building envelope can be determined.

Range of application: This technique has been mainly used in office block-type buildings where the movement of large volumes of air is needed to create the required pressure differentials.

However, the technique can be applied in any building where a suitable air-handling system is already installed. The criteria for suitability are that the system must be able to produce pressure differentials across the building envelope in the required range and that it must be possible to accurately measure the total air flow rate through the system when it is in operation.

Equipment and instrumentation: The essential equipment for this technique is a suitable air-handling system, some method of evaluating the air flow through it and a means of measuring the pressure differential across the building envelope.

Many types of ***air handling system*** are used in buildings. Before attempting this type of measurement in any building the suitability of the installed system must be assessed. This technique requires the system to be operated in a non-standard manner. Basically it must be possible to arrange the ventilation system so that the building becomes either pressurized or depressurized. In pressurization, for example, it must be possible to operate the supply fans while the return and exhaust fans are turned off. Return dampers must also be closed so that supply air flowing into the building can only leave the interior through outside doors, windows and other leakage sites. The system air flow rate must be controllable through an appropriate range by adjusting damper positions, fan speeds and/or the number of fans in operation.

It is recommended that the building services site engineer be consulted at all stages of the setting up procedure, thus making full use of detailed information about the operation of the air handling system.

Several methods are available for the ***measurement of air flow rates*** in ventilation systems. An examination of all these techniques is beyond the scope of this report and they are well documented elsewhere (See for example *[Svensson 1983]*). One particular technique will, however, be examined in detail. This method has been chosen for two reasons. Firstly because it has been applied successfully to internal fan pressurization measurements in a variety of buildings systems *[Persily, 1986]*, and secondly because it has been developed from the same principles as the constant emission rate method for evaluating building air change rates (see Part III Section 3.4).

Some air flow measurement methods require long straight sections of duct preceding and/or following the measurement plane. With these methods if there is insufficient distance between the measurement point and the nearest disturbance to the flow (e.g. bend, damper or fan), then large errors in the measurement results may occur.

If, however, a tracer gas is used for the measurement of air flow rate then the distance from the nearest disturbance to the flow becomes less critical. Indeed it can be an advantage to have induced turbulence at the measurement location. This is because the tracer gas method described here is most effective when a homogeneous mixture of air and tracer can be maintained.

The method is based on injecting a known flow rate of tracer gas into the ventilation duct, usually at the upstream side of the supply fan. Further downstream when the tracer gas has become well mixed with the air by the fan, the tracer concentration is continuously monitored. Under conditions of good mixing the air flow rate can be determined from the tracer injection rate and the measured concentration using:

$$q = \frac{s}{c_g} \tag{4.3}$$

where:

q Air flow rate through ventilation system m^3s^{-1},

s Injection volume flow rate of tracer into ventilation system, and

c_g Volume concentration of tracer in ventilation system.

If the air in the duct contains a certain initial concentration of tracer gas (this may occur due to recirculation via leaky return dampers, but should be avoided if possible) then a correction factor must be applied to the above equation, which becomes:

$$q = \frac{s}{c_g - c_{gd}} \tag{4.5}$$

where c_{gd} is the initial volume concentration of tracer gas in duct.

The gas flow rate can be measured with a calibrated float type variable orifice meter and the tracer concentration is evaluated using a suitable analyzer. In this way the flow rate through the ventilation system is calculated.

Setting up and operating details: The first task is to ensure that the air-handling system on site can be configured to enable an over-pressure or under-pressure to be created within the building. Ideally no air should return to the ventilation supply fan. A schematic of an ideal internal fan configuration for this method is shown in Figure 4.1. Once the system has been set up the flow measurement device, tracer gas or otherwise, is installed. Pressure differential measurement devices are then located. With large buildings such as those often examined by this method it is often preferable to measure the differential pressure at more than one location on the building envelope. This is because the larger the building the more the natural pressure differences caused by wind and temperature will vary over the envelope and it may be necessary to obtain an average value for this parameter.

The measurement at more than one location can be performed by having several instruments or by having a single measurement device linked to a variety of pressure taps via lengths of tubing and a pressure selection switch. The exact number and location of the pressure taps depends upon the building shape and size. They should cover a range in height and be placed on more than one side of the building.

By adjusting the outside air intake dampers, the intake dampers on the fan or the fan speed itself, the air flow rate can be set to the required level. Once steady-state conditions have been reached then measurements of the flow rate and pressure differentials can be made. Subsequent measurements are made after alterations to the flow rate.

A range of pressure differentials should be examined and the actual range available will depend upon the volume and leakiness of the building as well as the air moving capabilities of the fan. The final data obtained from the test consists of pairs of values of the air flow rate and average pressure differential across the envelope.

The presentation of the results of this type of measurement is very similar to that of pressurization tests performed using external fans. This will not be discussed further here. However, when using this measurement technique it may not be possible to achieve a pressure difference of 50 Pa across the envelope. Therefore if the air change rate of different buildings at the same pressure difference is to be compared, then a lower pressure differential may have to be used.

Measurement accuracy: Two main parameters are measured in this method, the flow rate through the ventilation system and the pressure differential across the envelope. The flow rate through the system is usually evaluated by an indirect method such as the tracer gas technique described in Section 6.8.3. If this method is used then tracer gas injection rates and tracer concentration must be evaluated. Using a calibrated flow meter it is possible to evaluate the tracer gas flow rate to an accuracy of 1 % and a good quality analyzer can be used to estimate the tracer concentration to 2 %.

Pressure differential measurements can be made with a variety of instruments and it should be possible to evaluate pressure differentials at individual points across the building envelope to 2 %. With large buildings there may be a range of pressure differentials existing across various points on the envelope and care must be taken when assigning a single value to this parameter. The variation of pressure differential can be minimized by making measurements under calm conditions and low temperature differentials. While no standard exists for the internal fan pressurization technique it is recommended that measurements be made when the wind speed is less than 2 m/s and the indoor outdoor temperature difference is not greater than 20 °C.

4.1.3. AC Pressurization

This technique evaluates the equivalent leakage area of a building envelope at pressure differentials similar to those created by natural wind and temperature effects.

Principle of the method: This technique uses a piston to create a continuous harmonic change of a building's internal volume. In turn this creates a fluctuating pressure difference across the building envelope *[Sherman and Modera, 1986]*. This can be distinguished from naturally occurring pressure fluctuations.

By measuring the amplitude of the pressure response inside the building, and the phase relationship between the pressure and the velocity of the piston the air flow through the envelope can be evaluated. Given this computed air flow and the measured pressure differentials the equivalent leakage area is determined directly.

Range of application: This technique has been used successfully in several domestic buildings with volumes in the range 300-500 m^3. Its only real limitation lies in its inability to measure large leaks such as undamped chimneys or partially open windows. Tests have shown that leaks over some critical size are treated by AC pressurization as though they were equal to that critical size.

Equipment and instrumentation: Any AC pressurization test apparatus must include components which perform the following basic functions:

Volume Drive: The purpose of the drive component is to provide a harmonic change in the internal volume of the building, at a known or specified amplitude and frequency. A frequency range of 0.2 - 4.0 Hz and a displacement range of 10 - 100 liters is adequate for residential buildings.

The displacement monitoring component should be able to provide an instantaneous value of the piston velocity. This is one of the two inputs used to compute the airtightness of the building. The type of displacement monitoring required will depend both on the drive component and the means by which it is driven.

Pressure Measurement: This component measures the instantaneous pressure response of the building to the induced volume changes. It is required only to measure the pressure signals at the drive frequency and its harmonics, other frequencies can be filtered out or eliminated with no loss of accuracy.

Analysis/Control: This component uses the velocity and pressure response signals to calculate and display the equivalent leakage area of the envelope. If automatic operation is desired then this component should be able to control the volume drive in order to attain a specified pressure response.

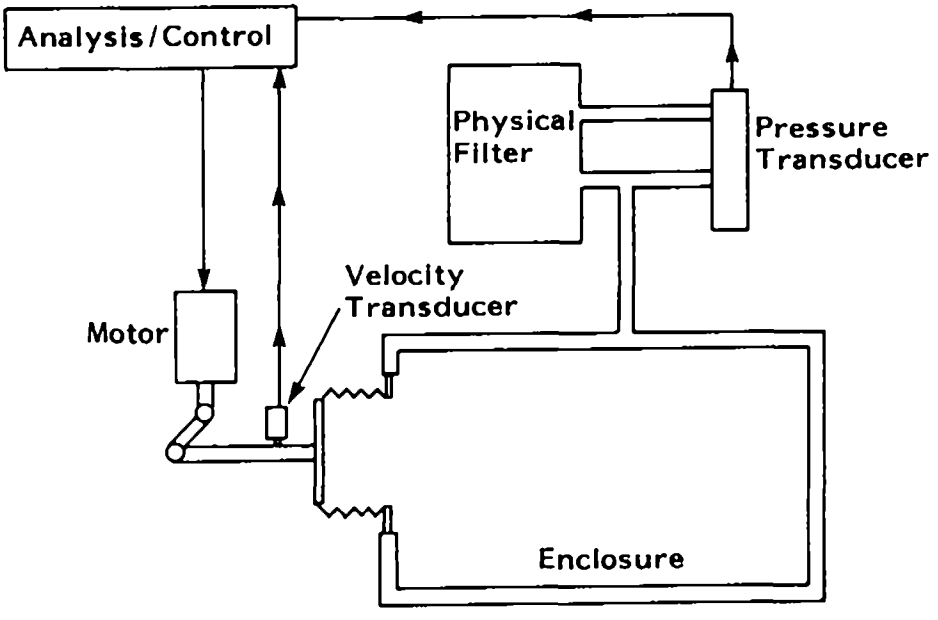


Figure 4.1.: Schematic of AC pressurization equipment [Modera and Sherman, 1985]

Specific Description of a Working Device: Several options are available for the accomplishment of each of the above named tasks. Several combinations of these options have been used to build working AC pressurization devices. Only one such device will be described in detail here (see Figure 4.1). This particular device is given attention because its viability has been proven in field trials, it is commercially available and it is similar to DC pressurization blower door equipment.

In this device the volume drive is provided by external bellows drive mounted in a door panel. A piston is connected to the flexible but airtight bellows and a scotch-yolk mechanism is used to turn the circular motion of a variable speed motor into true harmonic motion at the piston face. Mounting the device in a door panel facilitates portability and ease of location in the building envelope (See Figure 4.2).

The stroke of the scotch-yolk mechanism can be varied between 4 and 18 cm and this allows the volume drive to be adjusted between 10 - 15 liters. This displacement range has been found to be adequate for the testing of most domestic buildings.

By adjusting the speed of the DC motor the frequency of the device can be varied between 0.1 and 4 Hz. The speed of the piston is monitored by a wire-cable velocity transducer and the pressure response of the building is measured with a low frequency, AC-coupled condenser microphone which is sensitive to 0.01 Pa. Less expensive pressure transducers can be used instead of the low frequency microphone without loss of accuracy.

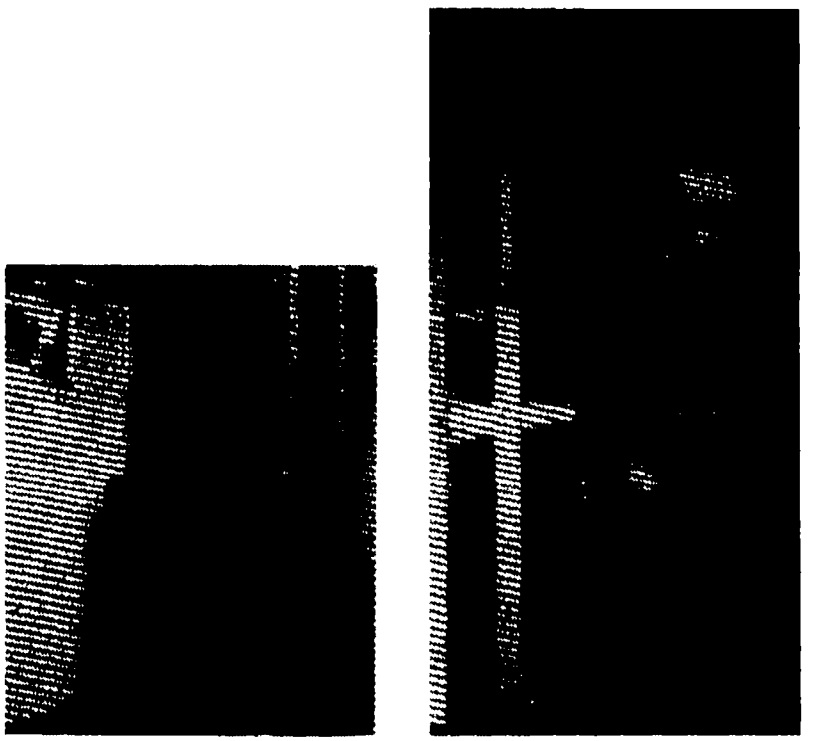


Figure 4.2.: Internal and external views of AC pressurization equipment [Modera and Sherman]

Setting up and operating details: The main setting up procedure consists of fitting the door panel into a suitable exterior door frame and placing the pressure measurement microphone inside the building. This procedure requires approximately the same time as required for installing a DC pressurization apparatus. The actual measurement time is short, approximately 3 minutes for a leakage area measurement. Tests have shown that the position of the microphone does not affect the measured pressure signal even when placed on the second floor of a two storey house. When preparing the building for the test it must be noted that there is a limitation to the size of leaks which will be detected by AC pressurization. So open windows and undamped chimneys may not be correctly evaluated.

Presentation of results: This technique evaluates the equivalent leakage area of the building envelope at a chosen reference pressure. The equivalent leakage area is determined by assuming that the flow through the envelope is similar to perfect orifice flow. The reference pressure is often taken as 4 Pa.

This pressure differential is often representative of pressure differences created by natural forces. Ideally when examining several buildings the results should be presented in a tabular format which includes other information about the building structure.

Measurement accuracy: The results by this relatively new technique have been compared with those obtained from the more well known DC pressurization method (blower door tests). This type of comparison has shown that the values for leakage area obtained by DC and AC pressurization agree reasonably well, but that the AC values are consistently lower than corresponding DC results. Because neither technique is a primary standard it cannot be determined which one is correct.

For example there may be systematic errors associated with DC pressurization due to the fact that leakage values quoted at low pressure differentials (e.g. 4 Pa) have been extrapolated from measurements made at much higher pressures.

However, AC pressurization might yield lower values than DC pressurization due to the effect of large leaks. In one test using the AC door panel the leakage through a window was measured as it was opened further and further. The results of this was that the measured leakage area increased with window opening up to a certain point after which the opening no longer affected the measured leakage area. This indicates that leaks over some critical size are treated by AC pressurization as though they were equal to that critical size. For the normal operating frequencies of AC pressurization the critical size of window opening is between 10 - 20 cm.

For some applications the measurement of large leaks is not required so this critical leakage area factor must be seen only as a limitation and not as an absolute disadvantage.

Comments: AC pressurization has several important advantages over its DC counterpart. It operates at pressures which normally drive infiltration. The measurement and analysis is done in real time, so the leakage area is measured continuously and essentially instantaneously, and only small volumes of air are exchanged with the atmosphere. The AC pressurization technique is also less sensitive to wind pressures than DC pressurization. This can allow measurements to be made under variable wind conditions without degrading accuracy.

Finally with a different choice of options for performing the volume drive, a device could be built which would perform AC pressurization without piercing the building envelope.Reproducible results, in agreement with pressurization tests were obtained on a relatively small volume.

4.1.4. Pulse pressurization

Principle of the method: The evolution of the pressure with time, during and after putting in the measured enclosure a puff of air, is a function of time which depends on the capacity of the enclosure and on its leakage characteristics. The dependance can be found by writing an energy balance for the enclosure, assuming that the energy losses are due only to leakage.

Range of application: since the method is still under development, its limits of application are not well known. An obvious limitation is that the pressure change due to leakage should be small during the transit time of sound waves across the enclosure.

Equipment and instrumentation: the pressurization equipment may not be required, since a pressure perturbation can be obtained by slamming a door. The instruments needed are a manometer able to follow the pressure decaying in a fraction of a second and a fast recording apparatus.

Example: Measurements were performed using the decaying part of the function, after slamming the door of a 25 m^3 cabin. Reproducible results, in agreement with pressurization tests were obtained on a relatively small volume *[Sherman and Modera, 1988]*.

4.2. Methods for Qualitative Evaluation of Components Leakages

4.2.1. Sound, Ultrasonic Leak Detection

This technique aims to detect air leaks by sound or ultrasonic transmission measurements. The technique ought to be applicable for in situ measurements using everyday sound level meters. An evaluation of the method showed, however, that the technique failed on two cases which occur very frequently in field measurements (foil-covered slits and slits coupled to damped cavities) *[Ringger and Hartmann, 1989]*.

Principle: The sound transmission through well-defined slits of various geometries (e.g. in a door) are measured (including slit covered with a foil). The sound pressures on both sides of the element are measured and their difference calculated:

$$\Delta p_s = p_1 - p_2 \qquad (4.5)$$

Where p_1 is the sound pressure level at 0.5 cm from slit and p_2 is the average pressure level in sender room.

A reference element without slits is used to correct for transmission through the door itself and a difference Δp_o similar to Δp_s has to be defined. Then the difference, $\Delta_{\Delta p} = \Delta p_s - \Delta p_o$, is used for the slit characterization.

Example: Tests were performed in a laboratory facility using a real-time 1/3 octave-band analyzer in the range from 200 Hz up to 10 kHz.

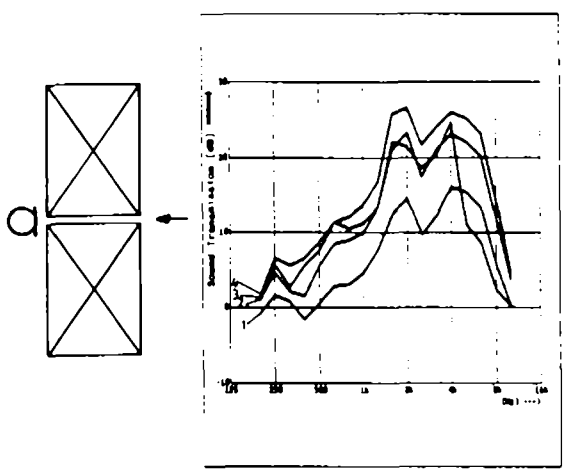


Figure 4.3.: Sound transmission T_s of simple slits: 1) 0.5mm; 2) 1.0mm; 3) 1.5 mm and 4) 2.0 mm. [Ringer & Hartmann, 1989]

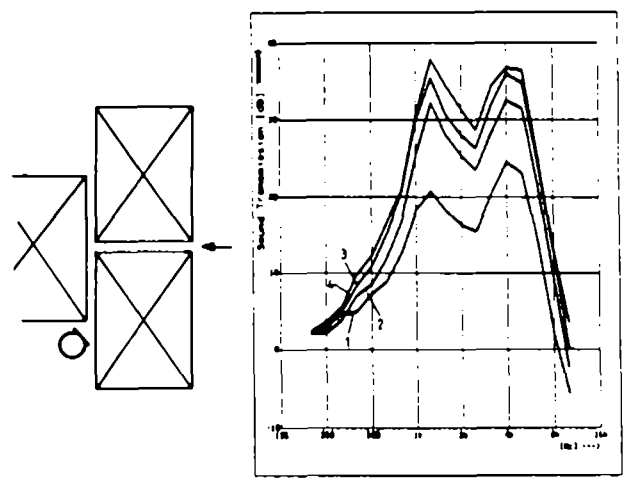


Figure 4.4.: Sound transmission T_s of slits containing a rectangular bend: 1) 0.5mm; 2) 1.0 mm; 3) 1.5mm and 4) 2.0mm.

A real time analyzer is not commonly available for field measurements. Therefore in the following table the linear or A-weighted sound level difference (calculated from the energetic sum of the 1/3-octave-bands) are presented:

Slit type	Level difference in dB (linear) (slit - reference beam)
simple slit	11.3
slit with rectangular bend	19.2
covered slit	12.4
slit coupled to damped cavity	1.4

It is obvious that the overall level differences are neither consistent nor reliable. The method fails because the relation between air flow and sound transmission is ambiguous.

List of required equipment:
- sender (e.g. white noise emitter),
- microphones,
- a-level weighted sound level meter or preferably a real time band analyzer.

4.2.2. Infrared Imaging and Depressurization

Local leakages can be visualized using infrared thermography in combination with a depressurized action of the building.

The method described is often used in combination with blower door measurements for the localization and qualitative characterization of distinct air leakage sources within a building.

Principle of the method: In order to detect leakage defects, the building is depressurized. The ingress of cold external air then cools the surfaces adjacent to the cracks. Thermal radiation, which depends on the surface temperature, is converted by the thermographic system to a visible thermal image.

For systematic tests, the building is depressurized using a fan. Less reliable results may be obtained by just relying on wind pressure. The method works best with temperature differences inside-outside above 10 K.

The quality of the thermal image may be improved using image processing systems. Thermal image interpretation requires a high level of expertise. The main difficulty lies in being able to separate air leakage path from other thermal irregularities in the envelope.

Nevertheless thermal images of surfaces cooled by infiltrating air very often may be identified by their typical tongue-shaped patterns.

Additional smoke tests may be required for leak verification.

Further reading on this method is to be found in *[Petterson and Axén]* as well as in several standards for thermographic building evaluation *[e.g. ISO 6781]*.

Example

Figure 4.5.: Thermographic image of surface areas cooled by air infiltrating through roof and wall-roof junction (dark stripes) [photo EMPA]

Figure 4.6.: Photographic picture showing the same room detail

List of required equipment:

- blower door/window,
- thermographic system with:
  - infrared camera (preferably with sensor range 8-13 μm),
  - image display monitor,
  - preferably image storage or video recorder and processing units;
- photographic camera for parallel pictures in the visual range and for the recording thermal image from the display screen.

4.2.3. Smoke Leak Visualization

To localize particular leakages in the building fabric smoke is used to visualize the paths followed by the leaking air when pressurizing the building. This method is often used in combination with pressurization measurements.

Principle of the method: Thermal imaging equipment is expensive and requires a high level of expertise to operate it effectively. The main difficulty lies in being able to separate air leakage paths from other thermal anomalies in the envelope, e.g. thermal bridges.

Smoke tests offer a cheaper and easier alternative for leak detection. Smoke can be produced in several ways, the most convenient often being a hand-held puffer and smoke stick (see Figure 4.7), and the technique simply involves pressurizing a building and using a smoke source to trace the paths followed by the leaking air. Smoke can also be used for flow Visualization through larger openings such as internal doors.

Example

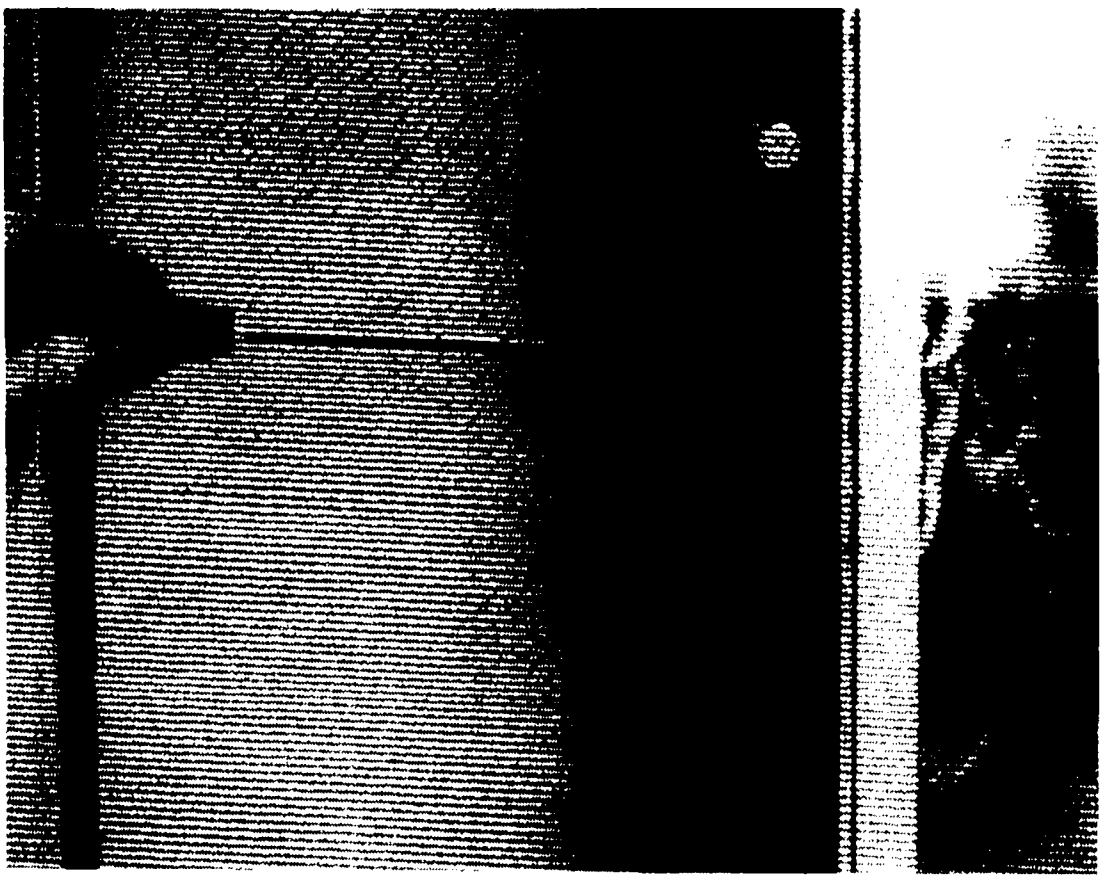


Figure 4.7.: Smoke Visualization [Dickson, 1981]

Required equipment: Hand-held puffer and smoke stick.

4.3. Methods for Quantitative Determination of Components Leakages

4.3.1. Direct Component Testing

This method aims to determine the air flow rate through a particular component (e.g. a window) by separating it from the rest of the building or by using a special test chamber in the laboratory.

For the latter application special standardized procedures for windows and doors exist in many countries.

Principle of the method: On site measurement of the leakage characteristics of an individual building component is done by pressurizing the component. This is done by pressing a half open airtight box with built-in fan against the component.

A normal pressurization test (see 4.1.1) is than executed.

Example

Important measurement errors may occur when the air flow is not one-dimensional. This is illustrated in the example of Figure 4.8.

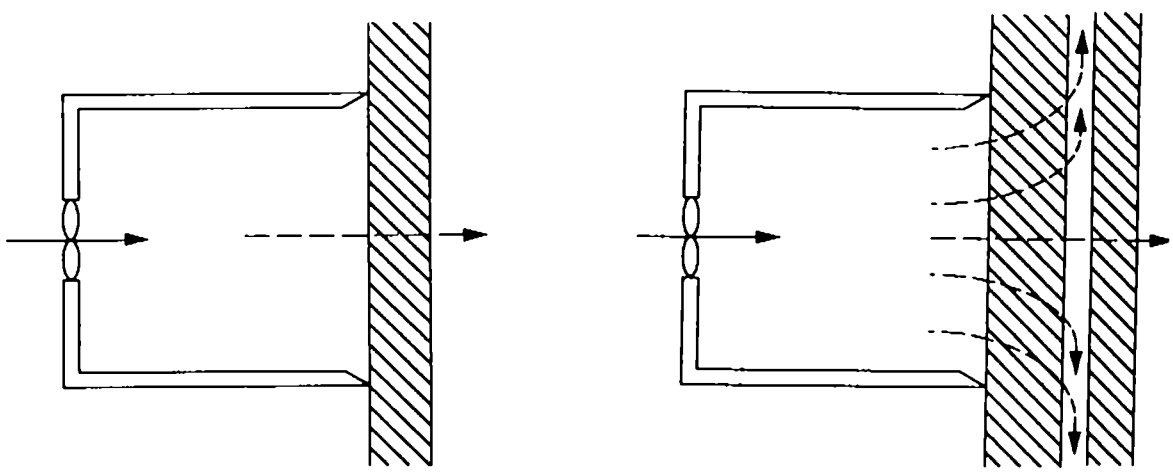


Figure 4.8.: Errors in the case of not one-dimensional flow through a component (part of a cavity wall)

Required equipment:

- collection chamber of appropriate dimensions,
- fan with adjustable speed,
- flow meter,
- pressure measuring device.

4.3.2. Indirect Component Testing by Reductive Sealing

A normal fan-pressurization test gives information about the airtightness of the whole building envelope but not about particular air leakage paths. This technique aims to quantify the proportion of the total air leakage which is attributable to different components or groups of components.

Principle of the method: The fan pressurization equipment is set up, and the dwelling prepared, in the usual way. If the dwelling is occupied it may be necessary to seal chimneys/flues but these can be sealed later as part of the test if desired. An air leakage test is then carried out, either pressurizing or depressurizing. A component or group of components is then chosen (e.g. all chimneys and flues) and sealed with self adhesive tape, polyethylene sheet, inflatable bladder or modelling clay, as appropriate. The air leakage test is then repeated, the difference between this test and the first test being a measure of the air leakage attributable to the component or group of components which were sealed.

An additional component, or group of components, is then chosen (e.g. the openable parts of all windows), sealed with tape, etc., and a further air leakage test carried out. The difference between this test and the previous test is a measure of the air leakage attributable to the components sealed between this and the previous test.

Further components can then be chosen and the process continued. Components which can usually be sealed include the following: chimneys, flues; ventilation openings; external doors (other than the one used to mount the pressurization fan); wooden ground floors; cracks between walls and floors; pipe and cable entry or exit points; and any other obvious cracks and openings (e.g. gaps between a window frame and the wall into which it is fixed).

The last air leakage test in this process gives a measure of the background air leakage, i.e. the remaining air leakage not sealed during the previous tests. It is quite common for this to constitute more than half of the overall air leakage, even where all of the most obvious air leakage paths have been sealed.

When all the components required have been sealed and air leakage tests carried out, the pressurization fan can be reversed and the air leakage tests repeated as the components are progressively unsealed in the reverse order to that in which they were sealed.

Best results are usually obtained by sealing groups of components (e.g. all openable windows in the dwelling) because the leakage through an individual component (e.g. a single openable window) can be too small for the pressurization fan to resolve. It is important that care is taken to make a good seal on all components. For example, on openable windows pay special attention to corners and around the fasteners.

Example: This method has been used to quantify the proportion of air leakage attributable to a number of air leakage paths in a single dwelling in an apartment building. The pressurization and depressurization measurements were done with the apartment as it was found, and then with the following component sealed:

1) all openable windows
2) two ventilation grilles in the kitchen
3) two external doors, to balcony and rear deck access
4) large holes in plasterboard (left by contractors examining the exterior concrete panel structure of the building) + service duct box (poorly fitting panels) + meter box (to seal of entry of electricity cables)
5) principal cracks (i.e. window frame/wall joints, external wall/ceiling joints, external wall/party wall joints, joints in wooden stairs adjacent to envelop wall).

The results of these measurements are presented in Figure 4.9. There are a number of points worth nothing. The windows were poorly fitting and were not draught proofed but only contributed about a third of the total air leakage. The large holes in the plasterboard were expected to make a large contribution to the overall air leakage but were found to be virtually airtight. The principal cracks, which were all easily visible and were each approximately 0.5 mm or more wide were a significant source of air leakage in contrast to the large holes in the plasterboard.

List of required equipment:

- one pressurization fan system with air flow measuring device,
- sealing materials such as duct tape, polyethylene sheet, inflatable bladder, modelling clay.

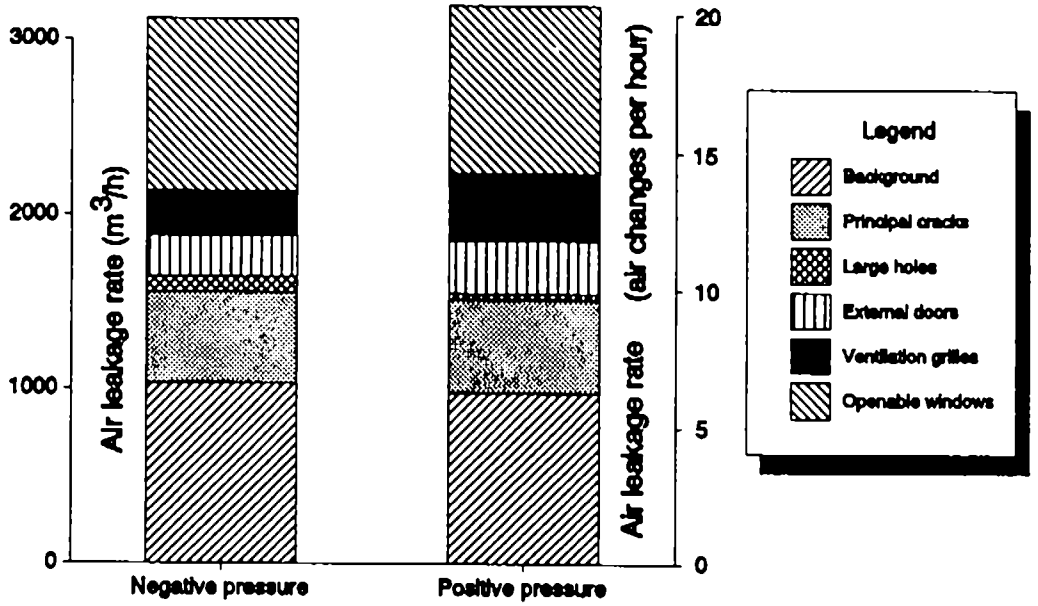


Figure 4.9.:Distribution of air leakage in an apartment by reductive sealing, at 50 Pa pressure difference.

4.3.3. Multifan Testing and The Guard Zone Technique

This method uses two fans and a control system to determine the leakages of various parts of the building. To avoid the tedious work of covering with a plastic foil the building parts which are not to be measured, the air flows through these parts are inhibited by maintaining a zero pressure difference through them.

Principles of the method: A measuring fan with its flow meter equipment is installed in a wall or door of the room containing the element to be measured. Another larger fan is installed in a door or a window of the building (or the dwelling) containing the room (Figure 4.10).

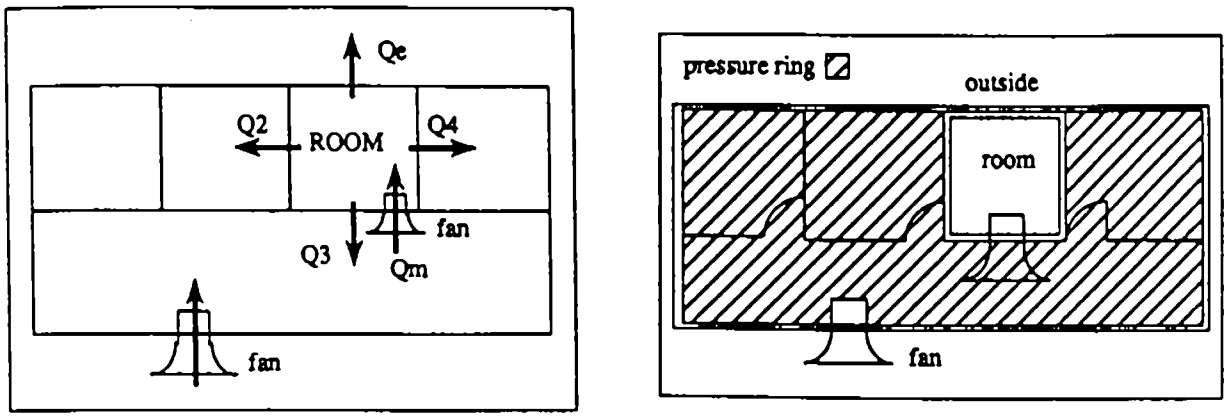


Figure 4.10: Principle of the guard zone technique applied to several walls of a room. The hatched zone is the guard zone.

In order to get the leakage characteristics for a given element, that is C and n in:

$$Q = C\,\Delta p^{n} \tag{4.6}$$

where Q is the air flow rate through the element under a pressure drop, Δp, through it, the pressure in the room should be varied step by step from 20 up to 60 or 70 Pa. The guard pressure should be varied simultaneously to maintain an average pressure difference, $\Delta p' = 0$, between the room and the dwelling. This pressure difference actually varies between -1 and +1 Pa. A fit through several measurements allows one to calculate the air flow, Q, corresponding to a zero pressure difference.

Other experiments can be used to measure the other walls of the room by opening or closing various doors and windows. When a set of measurements is done, enough equations can be written to compute the air flows through the various measured parts for each pressure step.

For that purpose, a second condition shall be fulfilled: in each measurement, the pressure in the room should be varied step by step from 20 up to 60 or 70 Pa. The guard pressure should be varied simultaneously to maintain an average pressure difference, $\Delta p' = 0$, between the room and the dwelling. This pressure difference actually varies between - 1 and + 1 Pa. A fit through several measurements allows one to calculate the air flow Q corresponding to a zero pressure difference.

Since even this control cannot be good enough to get accurate measurements (because of external and random influences such as temperature or wind fluctuations), the data are automatically selected and recorded only if several conditions are fulfilled:

- the pressure in the room is equal, within a pre-defined tolerance, to the pre-defined value of the pressure for each step,
- the pressure difference between the room and the guard zone is smaller (in absolute value) than a predefined small value.

Finally, for each pressure step and each configuration, several values are measured and averaged to minimize the effect of random noise.

Example: The computer-controlled MAGE system *[Fürbringer, Roecker, Roulet, 1988]* was used to measure the leakage distribution of the LESO building (fig. 4.11). Some results are given in the Figure 4.12.

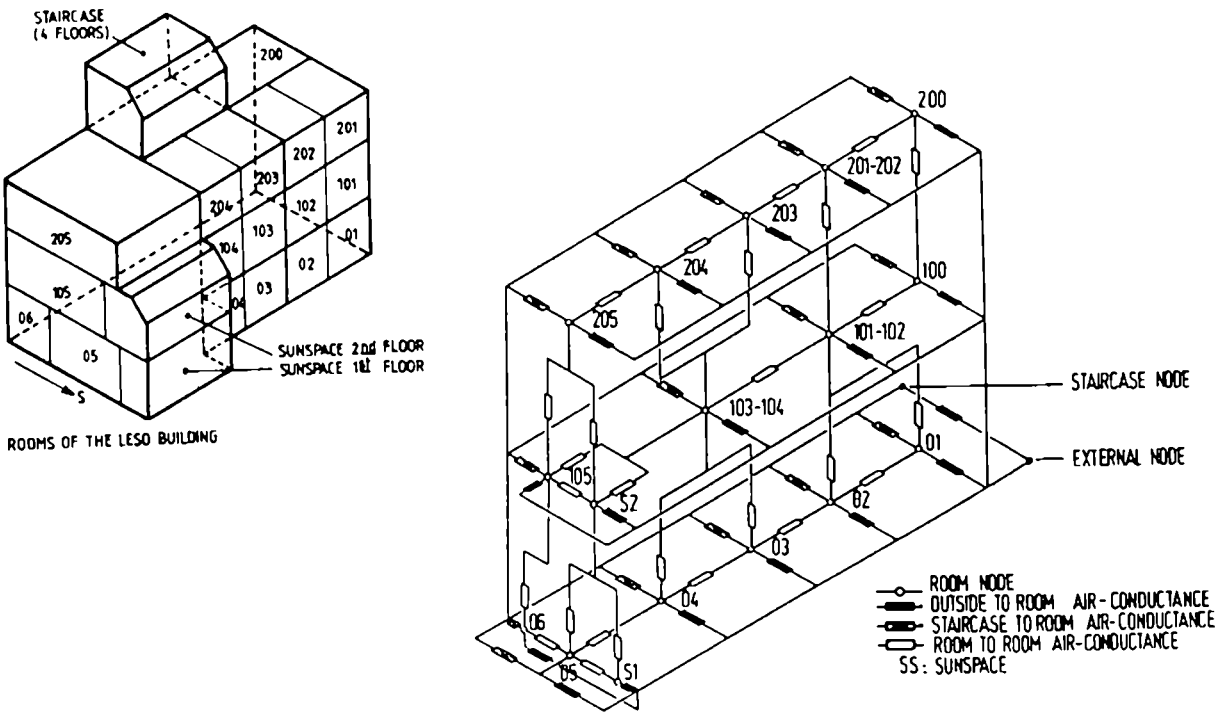


Figure 4.11: Nodal model and schematic perspective of the LESO building

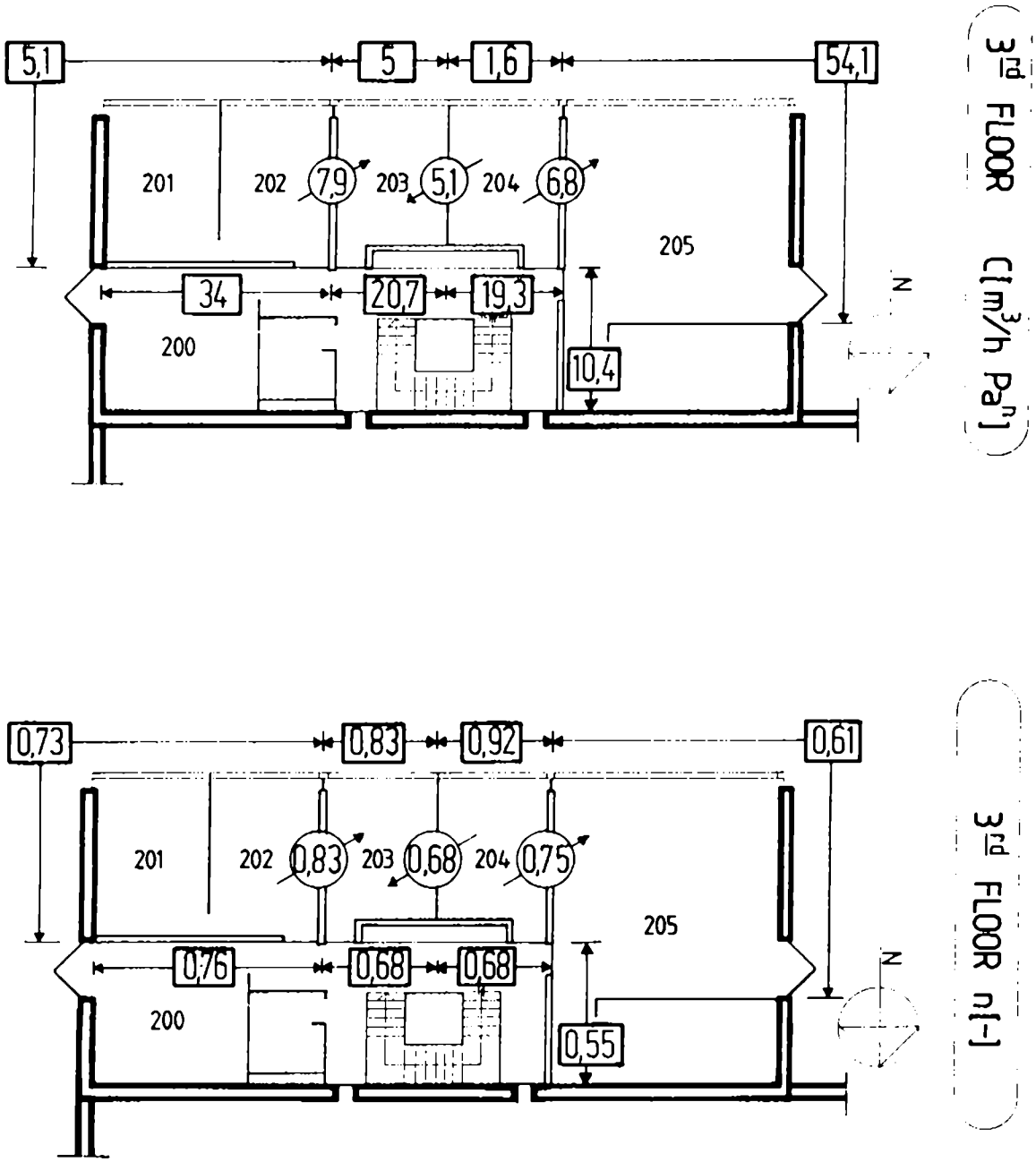


Figure 4.12: C [$m^3/h\ Pa^{2/3}$] and n values for several elements of the 3rd floor in the LESO building

List of required equipment

2 fans with their flow-metering devices
2 differential manometers 0-100 Pa
1 personal computer
2 air thermometers
1 anemometer (optional)
2 fan controllers and power supplies
1 differential manometer 0-10 Pa
1 data logger
1 barometer
1 hygrometer (optional)

4.3.4. Pressure Equalization

This method is a special case of the guard zone technique, particularly well suited for row houses. A proportion of the total air leakage measured in a fan pressurization test may not be to outside but across separating (or party) walls and floors to adjacent dwellings. Under natural conditions, such leakage is usually relatively unimportant to ventilation. This technique aims to quantify the magnitude of such leakage paths *[Stephen, 1991]*.

Principle of the method: One fully instrumented pressurization fan system is set up in the normal way to pressurize the dwelling of interest, house *B*, and another fan is set up to pressurize an adjacent dwelling, house *A*, (Figure 4.13). A second micromanometer is used to indicate the pressure difference between the two houses.

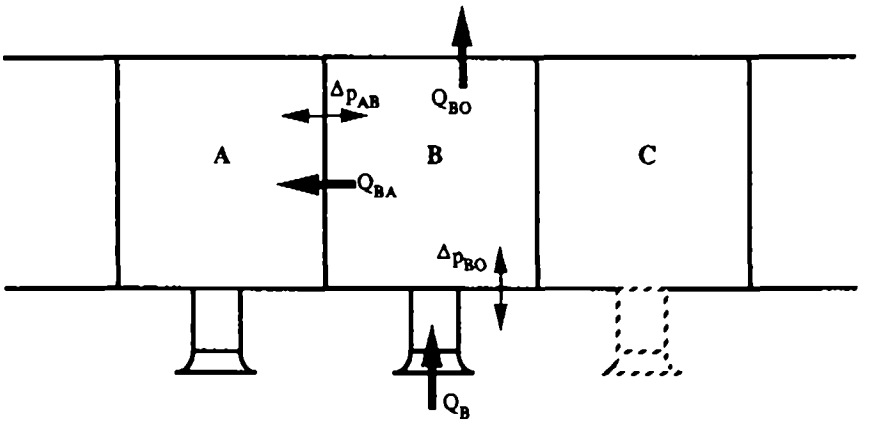


Figure 4.13: Inter-dwelling air leakage measurement - pressure equalization

The experiment can be conducted by two different ways. In the **simple pressure equalization** technique, an air leakage test is first carried out in house *B* in the usual way (fan in house *A* off). The test in house *B* is then repeated but with the fan in house *A* running such that whenever readings are taken there is no significant pressure difference between the two houses. This can normally be done to within 1 Pascal.

In the first test, there is a pressure difference, and therefore an air flow, across the party wall; but in the second test the pressure across the party wall is equalized and there is no significant air flow. The difference between the first and second tests is therefore the air leakage characteristic of the party wall between the houses *A* and *B*. The two fans can be turned around to measure the party wall air flow in the opposite direction too.

In the **progressive pressure equalization** technique (also called "deduction method" in Section 5.3), the house *B* is pressurized at 50 Pa and the house A is pressurized stepwise in order to change the pressure difference through the party wall. During the test, the fan *B* should be adjusted to maintain 50 Pa. The properties of the party wall are obtained by fitting the leakage characteristic curve on the measured pressure differentials between *A* and *B*, Δp_{AB}, and the measured air flow rate through fan *B*. The air leakage curve for the party wall is obtained by subtracting the air flow rate, Q_0, through fan *B* with $\Delta p_{AB} = 0$, from the fitted curve.

The data obtained from the above tests may be analyzed using either the usual power law fit or the less widely used quadratic curve fit (equations 2.1 and 2.2).

In principle, the value for Q_0 is the smallest of the measured flow rates through fan *B*, when $\Delta p_{AB} = 0$. The value of Q_0 is however better found by an identification method. If the quadratic curve fit is used, Q_0 is found by solving the equation 2.2 with $\Delta p = 0$. If the power law is used, it could rewritten as:

$$Q_B = C\,\Delta p^n{}_{AB}{}^n + Q_0$$

and this is iteratively fitted on the measured data, varying Q_0 until the best correlation is found.

Where another adjacent dwelling exists, *C* in Figure 4.13, the above procedures can be repeated to measure the inter-dwelling air leakage between *B* and *C*, and similarly in flats to dwellings above and below. In theory, given a sufficient number of pressurization fans, it should be possible to control the pressures across all party walls and floors simultaneously. However, in practice controlling two fans can be difficult and setting up and controlling three or more fans at once would be impractical.

The accuracy of fan pressurization measurements is important to this technique because inter-dwelling

air leakage measurements place great demands on a technique which is already subject to errors from a number of sources (see Appendix 4). Interpretation and use of inter-dwelling air leakage data from tests carried out in anything other than ideal weather conditions should therefore be treated with some caution. Progressive pressure equalization tests are particularly difficult to carry out because changes in air flow rate between successive measurement points are very small. Small deviations from the 50 Pa pressure difference generated by fan B can significantly mask the changes in air flow rate, so very careful control of this fan is necessary.

List of required equipment

- one pressurization fan system with air flow metering device,
- one pressurization fan without air flow metering device,
- two differential pressure manometers (0 - 100 Pa, with resolution 1 Pa maximum),
- computer/programmable calculator.

Example: Inter-dwelling air leakage measurements were carried out under ideal conditions in the terrace of three BRE experimental houses (*A*, *B*, and *C*) which are typical of modern British timber framed construction. Houses *A* and *C* are the end terrace houses. The results of both types of pressurization tests are shown in Table 4.1. and 4.2 .

Leakage direction	Normal test Power fit Q [m^3/h]	Wall leak Power fit Q [m^3/h]	Normal test Quadratic Q [m^3/h]	Wall leak Quadratic Q [m^3/h]	Percent wall leak Power fit	Quadratic
Measurements based in house A (Leakage between A and B)						
A to B	2147	395	2133	380	18.4	17.8
B to A	2122	368	2103	366	17.3	17.4
Average	2135	382	2118	373	17.9	17.6
B to A again	2129	296	2114	281	13.9	13.3
Measurements based in house B (Leakage between B and C)						
B to C	2889	368	2887	353	12.7	12.2
C to B	2746	406	2712	394	14.8	14.5
Average	2818	387	2800	374	13.7	13.4
C to B again	2685	327	2658	313	12.2	11.8

Table 4.1: Inter-dwelling air leakage rates at 50 Pa pressure difference by the simple pressure Equalization method

Leakage direction	Wall leak Power fit Q [m^3/h]	Wall leak Quadratic Q [m^3/h]	Wall leak as a percent of the house Power fit	Quadratic	Wall leak as a percent above or below pressure equalization Power fit	Quadratic
Leakage between A and B						
A to B	268	466	13	22	-32	+18
B to A	[285]	423	13	20	-23	+15
Average	277	445	13	21	-27	+16
B to A again	[246]	308	12	15	-17	+4
Leakage between B and C						
B to C	[331]	382	12	13	-10	+4
C to B	374	412	14	15	-8	+2
Average	353	397	13	14	-9	+3
C to B again	[334]	441	12	17	+2	+35
Note: Figures in brackets [ ] indicate that iteration did not run to optimum air flow rate intercept. In these cases, Q_0 is assumed to be the minimum measured Q_B minus 1 m^3/h						

Table 4.2: Inter-dwelling air leakage rates at 50 Pa pressure difference by the progressive pressure Equalization method. The inconsistency of the results in this table reflects the difficulty encountered whilst taking the measurements.

4.3.5. Compensated Flow Meter

Multifan testing as described in 4.3.3. requires several fans and manometers, and is often very time consuming. The use of a compensated flow meter can simplify significantly the determination of the leakage distribution. It allows for the measurement of the flow rate through the envelope between a guarded zone and the outside.

The principle of the method is the guard zone method as described in 4.3.3. The compensated flow meter (fig. 4.13) contains a pressure vane measuring the pressure difference across the compensated flow meter. The control of the compensated flow meter is limited to adapting the fan speed so that this pressure difference becomes zero. The flow rate can then directly be read from the position of the control knob.

The two main advantages are:

- built in manometer,
- direct reading of the flow rate (this is possible since in this case there is a direct relation between the fan speed and the flow rate).

In practice, the measurement can be done by using a light wooden panel of dimension somewhat larger than the inner doors. There is a hole in the panel which is smaller than the opening of the compensated flow meter. The panel is pushed against a door opening (door open). The main fan pressurizes (or depressurizes) the building and the compensated flow meter is then adjusted so that the Δp-reading becomes zero. The indicated flow is the flow between that zone and the outside. This requires of course that all inner doors are open.

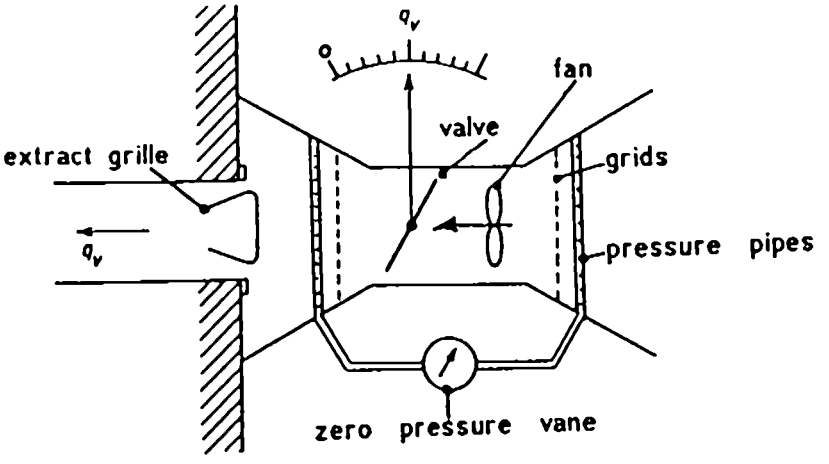


Figure 4.14.: Schematic cross-section of flow meter showing measurement principle [Phaff, 1987]

Discussion: Some precautions are needed when applying the compensated flow meter technique.

- This technique gives good results in situations where the air leakages between the tested room and the outside are larger than between the building and the tested zone. In the opposite situation even a small pressure unbalance between building and tested zone may introduce large errors.
- It is very important to have an as large as possible opening in the wooden panel. Indeed, if the opening section is small, there might be a pressure difference across the wooden panel, ΔP_w, resulting in a pressure difference between the building and the tested zone (fig. 4.14).

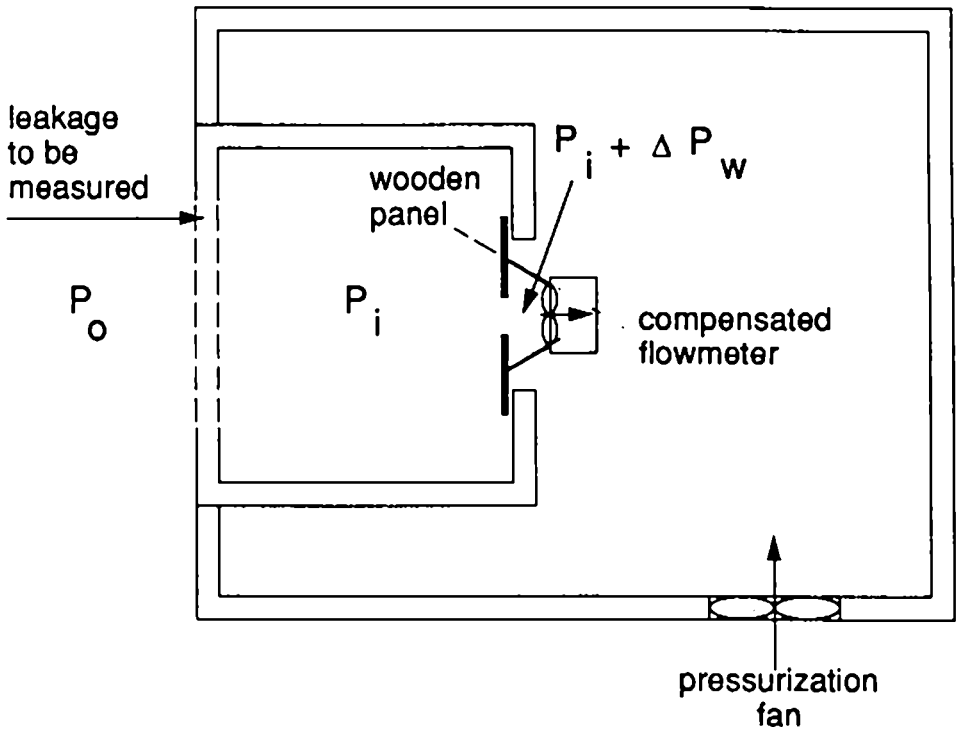


Figure 4.15.: Compensated flow meter applied to small openings

Table 4.3 gives an indication of the measured errors as a function of flow rate and dimensions of the opening.

	Opening section (cm)		
Flow (m3/h)	**5 x 5**	**25 x 10**	**39.5 x 30.5**
10	2.2	0	0
50	46.4	- 0.06	0
220	198	- 8	2

Table 4.3. Measured errors on pressure difference readings (Pa)

List of required equipment

Ordinary fan for whole building pressurization
Compensated flow meter.

4.3.6. Combination of Pressurization and Tracer Gas Techniques

The leakages are determined by simultaneous use of tracer gas and pressurization equipment.

The air leakage distribution in a building is, in certain circumstances, difficult to determine. One example of this is the ceiling of the dwelling illustrated in figure 4.16. Testing the ceiling air tightness by reductive sealing is not normally practical and similarly, the guard zone technique is difficult to apply in this case. A rather simple and easy technique is to perform measurements using tracer gas and pressurization equipment at the same time.

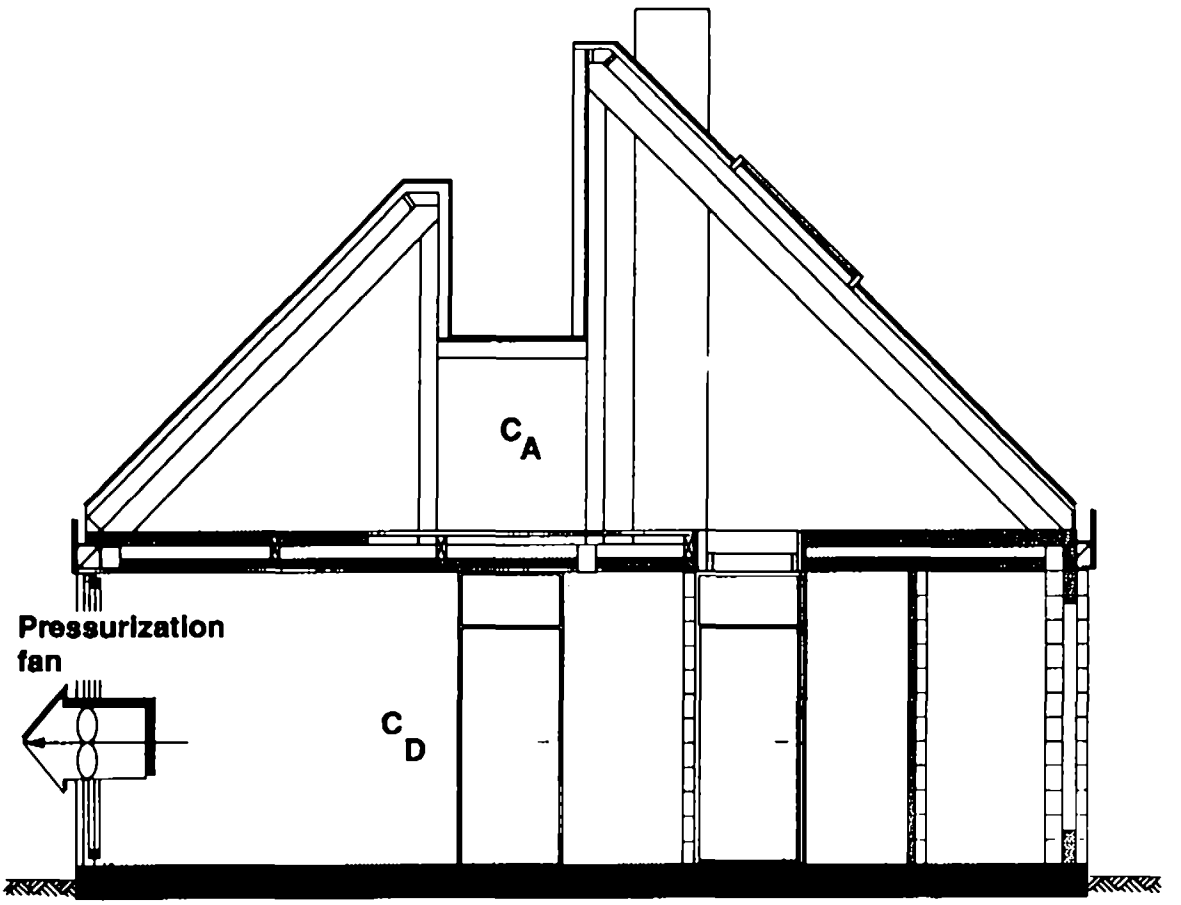


Figure 4.16. Cross section of test house

Principle of the method: A approximately constant concentration of tracer gas in the attic should be maintained during the measurement. This can be done by using constant concentration equipment or by using the constant injection technique if the weather conditions are stable. Since the leakage rates to the outside are usually high, use of small mixing fans is recommended.

The dwelling is maintained under depressurization, for example $\Delta P_{ie} = 50$ Pa.

The tracer gas concentrations are measured in the attic and in the entrance of the pressurization door. Let C_D be the concentration in the dwelling and C_A the concentration in the attic. It is clear that the tracer gas measured in the dwelling is coming through the leakages in the ceiling. Therefore:

$$\frac{\textit{Leakage in the dwelling}}{\textit{Leakage in the ceiling}} = \frac{C_D}{C_A} \qquad (4.7)$$

The leakage (ie. leakage air flow rate at ΔP_{ie} or equivalent leakage area) in the dwelling can be obtained from a global pressurization measurement, so that the leakage of the ceiling is determined from:

$$\textit{Leakage in the ceiling} = \frac{C_A}{C_D} \quad \textit{Leakage in the dwelling} \tag{4.8}$$

It is obvious that this relation is theoretically only valid for the pressure differential, ΔP_{ie}, used during the measurement. The results are only valid if a good mixing of the tracer gas in the attic can be obtained.

The principle is based on steady-state conditions. One can show that these are almost fulfilled after 2 τ_n hours (τ_n = nominal time constant during the pressurization test).

This means that for a dwelling with a n_{50}-value of 5 h^{-1}, τ_n = 0.2 h, and the measurements can be started after 2 x 0.2 hour or 24 minutes. For very airtight houses, τ_n is high and the boundary conditions will not remain constant during the measurement. Therefore, a non-steady-state analysis may be necessary for such buildings *[Sherman and Modera, 1986]*.

List of required equipment:

- pressurization equipment,
- tracer gas, gas analyzer,
- pressure transducer.

Example: Table 4.4 shows results obtained in two identical houses at the Belgian Building Research Institute.

	% of leakages	
	ceiling	floor
dwelling 1	16	22
dwelling 2	28	17

Table 4.4: *Leakage area in the attic and the cellar as a percent of the whole house for two dwellings* (n_{50} = 10 h^{-1})

4.3.7. Stack Effect Method for High Rise Buildings.

This simple and easy-to-install method to estimate the air leakage distribution in tall buildings is based on the pressure distribution induced in buildings by the stack effect *[Tamura and Wilson, 1966]*. Three parts can be estimated separately: the ground and top floors and the remaining floors.

The basic idea is to pressurize the building with the stack effect, and to plan three different experiments where two air flows can be measured to get three independent equations for the three different leakages which will be estimated *[Hajakawa and Togari, 1989]*.

Principle of the method: the building should be tall and the temperature difference between indoors and outdoors should be large enough, in such a way that the pressure difference between inside and outside induced by the stack effect is larger than the pressure caused by the wind. Such a pressure difference may reach 30 [Pa] if the product of the height by the temperature difference overpasses 700 [K.m].

The leakage of the building is divided into three parts:

- leakage through the ground level including the entrance door (suffix *g*),
- leakage through the top level including the roof (suffix *t*),
- leakage through the remaining floors (suffix *r*).

If the building has all its internal doors open as well as the staircase and/or the lift shaft and if the temperature does not vary too much throughout the building, there is a priori only one neutral plane at the height z_0. The pressure difference caused by the stack effect at any height in a given building configuration is then:

$$\Delta p(z) = \int_{z_0}^{z} \Delta\rho(z)\, g\, dz \tag{4.8}$$

If the temperatures are homogeneous, equation (4.8) gives:

$$\Delta p(z) = \Delta\rho\, g\, (z - z_0) \tag{4.9}$$

From the law of perfect gases:

$$\rho = M\, p/(RT) \tag{4.10}$$

Combining (4.9) and (4.10), we get:

$$\Delta p(z) = \frac{M\, p}{R} \left[\frac{1}{T_i} - \frac{1}{T_e} \right] g(z - z_0) \tag{4.11}$$

The leakage of the building is represented by the usual power law:

$$Q = C\, \Delta p^n \tag{4.12}$$

Assuming that the exponent n is constant for all the leaks, there are three unknowns, the leakage coefficients, C_g, C_r and C_t. To estimate these coefficients, three measurements, where the pressure differences, the temperatures at various height in the building and some air flows are measured, are performed. A first relationship is given by the conservation of mass with a closed envelope. The two other equations are obtained by mass conservation with a large opening at the bottom and at the top of the building. In these cases, the air flows through these openings shall be measured. The relations are as follows:

1 - All openings closed: In this case, the neutral plane is somewhere at mid-height of the building and, by conservation of the mass of air, we have:

$$\rho_g\, C_g\, \Delta p(z_g)^n + \int_{z_{rb}}^{z_{rt}} d(\rho_r\, C_r\, \Delta p(z_r)^n) + \rho_t\, C_t\, \Delta p(z_t)^n = 0 \tag{4.13}$$

where ρ_g, ρ_r and ρ_t are the densities of the air to take into account at the ground level, the remaining floors and the top level in order to have the proper mass flow.

2 - Entrance door open: The air flow through the open entrance door (or any other large opening on the ground level), Q_g, is measured, for example by measuring the air speed at several locations and integrating over the whole opening.

$$\rho_g Q_g + \int_{z_{rb}}^{z_{rt}} d(\rho_r C_r \Delta p(z_r)^n) + \rho_t C_t \Delta p(z_t)^n = 0 \qquad (4.14)$$

3 - Windows open at the top level: The air flow through these windows, Q_t, is measured. We have similarly

$$\rho_g C_g \Delta p(z_g)^n + \int_{z_{rb}}^{z_{rt}} d(\rho_r C_r \Delta p(z_r)^n) + \rho_t Q_t = 0 \qquad (4.15)$$

The neutral plane is now at the top level.

Assuming that n is 0.6, or 2/3, which are most probable values, the system of the equations (4.13 to 4.14) can easily be solved to estimate C_g, an global C_r and C_t. If the temperatures are not uniform inside or outside, equation (4.8) should be used instead of equation (4.9). The system is then more complex but can still be solved. The most important condition to observe during the measurement is the absence of wind.

Required equipment: The main advantage of the method is that it does not require the use of sophisticated equipment. As a minimum, the required equipment is:

1 wind velocity meter, 0-5 [m/s]
2 differential manometers 0-50 [Pa]
3 air temperature thermometers
1 length measuring device.

This minimum equipment can be completed by at least two more differential manometers and two more thermometers. These additional instruments are used to verify the linearity of the pressure distribution through the building.

Tracer gas equipment may also be used to measure the air flow through the openings.

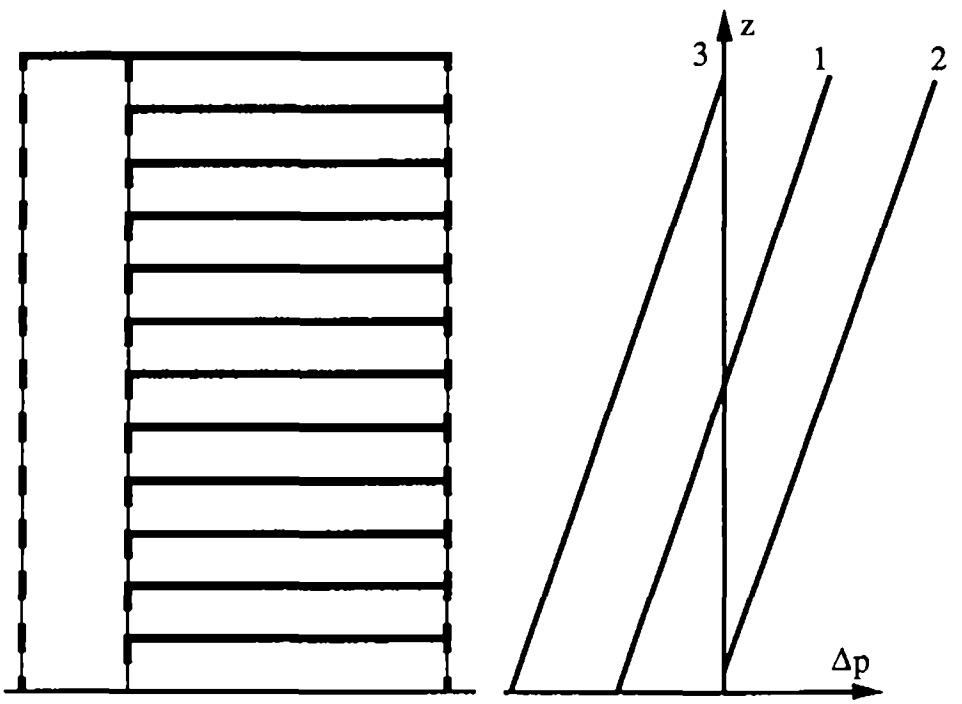


Figure 4.17: The building is represented to the left. To the right, the pressure distributions for the three experimental cases are given: 1) closed building envelope; 2) ground floor door open; 3) top level window(s) open.

5. Treatment of Results

5.1. Procedure for Leakage Distribution Measurements

The procedure to follow for the determination of the leakage coefficients for a multizone building (that is, a network of leakages) is shown schematized on Figure 5.1.

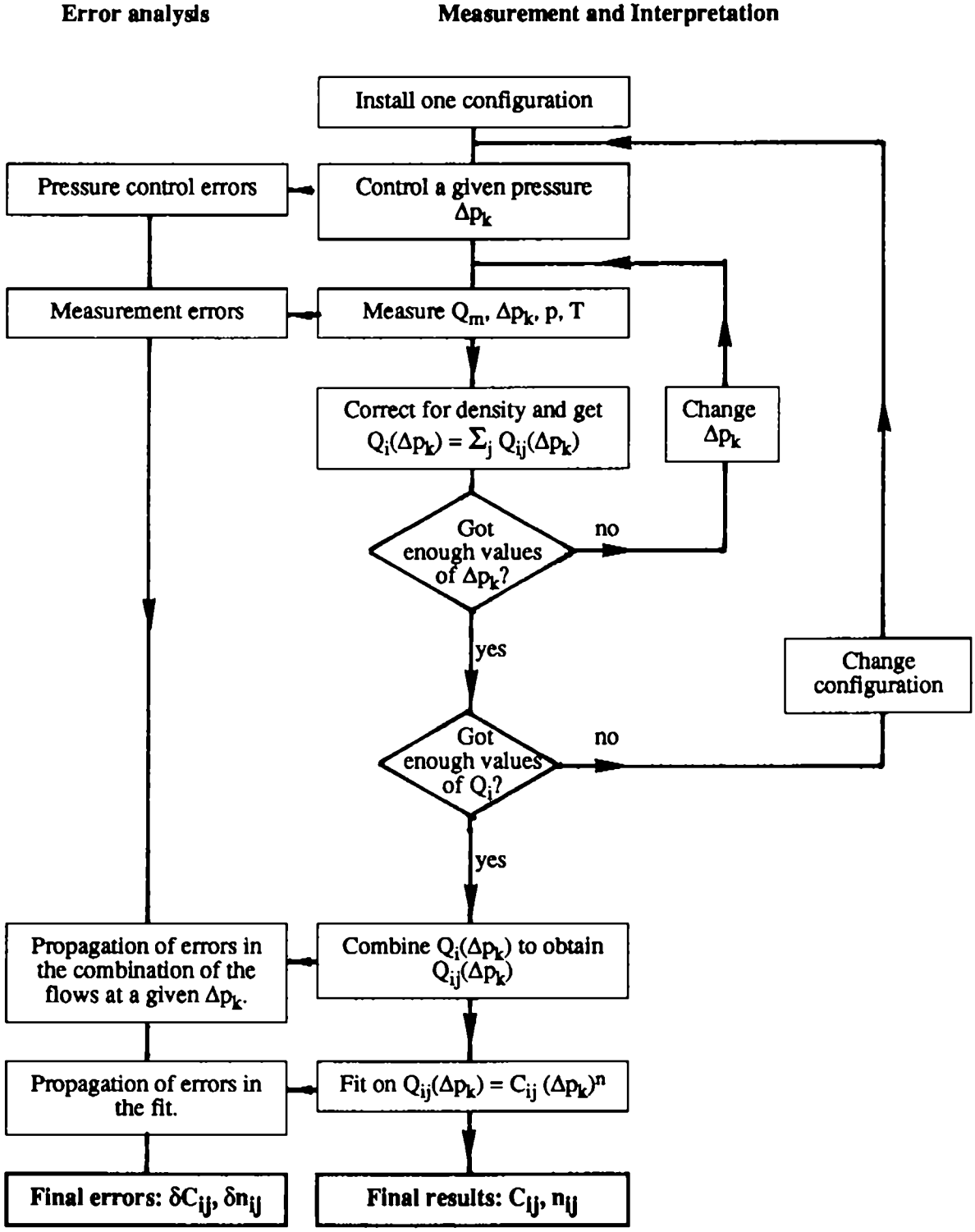


Figure 5.1: Procedure for the determination of the leakage distribution and the corresponding errors.

In this chapter, the interpretation of the measurements to get the leakage parameters and the corresponding error analysis are described.

5.2. Mass Balance Equations, Density Corrections

Most of the air infiltration models of a building use relations between the air flow rate, q [m^3/s or m^3/h], and the pressure difference, Δp [Pa], across a building element *[Liddament, 1986]*. These relations are either:

$$q = C\,\Delta p^n \tag{5.1}$$

or:

$$\Delta p = a\,q^2 + b\,q\,(+\,c) \tag{5.2}$$

It is hence necessary to deduce the coefficients, C and n or a, b and c from measurements. In a single zone building, this is done by pressurizing or depressurizing the building element with a fan and measuring as well the pressure difference between the zone and the outdoor air as the air flow rate q_m through the fan. Fitting the measurements for at least two different pressures using equation (5.1) or (5.2) gives the required coefficients *[Dickson, 1981]*. However, it is the flow through the fan, q_m, which is measured and the flow, q, through the leak which is needed to calculate the leakage coefficients. In a steady state, the mass of air is conserved and:

$$\rho_m\,q_m = \rho\,q \quad \text{hence} \quad q = q_m\,\rho_m/\rho \tag{5.3}$$

where ρ_m and ρ are the densities of the air going respectively through the fan and through the measured element. Using the law of perfect gases, the density of the air can be expressed as:

$$\rho = \frac{M\,p}{R\,T} \tag{5.4}$$

where:

M is the average molecular weight of the air, that is 0,02894 [kg/mole]

p is the atmospheric pressure [Pa]

R is the constant of the perfect gases: R = 8.31396 [J/mole.K]

T is the absolute temperature [K]

Since the pressure and molecular weight are nearly the same for q and q_M, equation (5.3) becomes finally:

$$q = q_M\,T/T_M \tag{5.5}$$

where T and T_M are the absolute temperatures of the air going respectively through the measured elements and through the fan or the air flow measuring device. Before any further analysis, equation (5.4) should be used to correct the measured flows.

5.3. Obtaining the Air Flow Distribution for One Pressure Difference

5.3.1. General Procedure

In principle, the measurement of flow characteristics of each leakage path can be made by using an enclosure (e.g. a plastic bag) to pressurize one side of the measured element or building partition. In a usual building, generally inhabited, it is quite impossible, and at least very tedious, to install this enclosure on all the conductances.

When pressurizing one zone of the building, the air coming from the fan or the air flow measuring device flows through a combination of the leakage paths to be measured. By opening some doors or windows, it is possible to impose the same pressure to different zones, or in other words, to make different parallel arrangements of leakage paths. If the measurement of leakage paths in series is avoided and only parallel arrangement is allowed, the total mass air flow rate, Q_i, from zone i at a given pressure difference is the sum of the individual air flows, Q_{ij}, from zone i to zone j:

$$Q_i = \sum_{j \neq i}^{j} Q_{ij} \tag{5.6}$$

The index j runs from 0 (outside air) to the number of zones, N.

It is important to avoid serial arrangements of leakage paths, since such arrangements result in non-linear equations. Using two or more fans, it is also possible to suppress some flows. The operation is then repeated by pressurizing successively various zones at the same pressure in order to get enough equations (in principle $N(N+1)$) to have a solution of the system (5.6). That way, we get a set of $Q_{ij}(\Delta p)$ for a given pressure difference, and an error analysis gives the standard deviations, $s(Q_{ij})$.

Note that all these measurements should be conducted at fixed pressure differences, to get all the Q_{ij} for these pressure differences. Practically this condition requires an automatic control of the pressure differences.

The procedure should be repeated at other pressure differences. For each leakage path for node i to node j, we will have several values of the air flow rates, Q_{ij} for several pressure differences, together with their standard deviations or confidence intervals. The procedure described in Section 5.4, applied to these values and using equation (5.1) or (5.2) gives the desired coefficients.

The detailed example given in Appendix 4 may clarify the described procedure in cases where two fans are used (fig. 5.1). In this example, two techniques commonly used for multizone leakage characteristics measurement are used: the so-called deduction method and guard zone method.

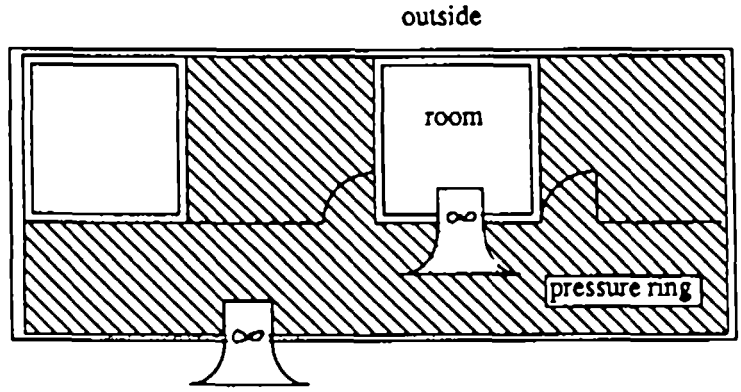


Figure 5.1: Example of the measurement situation when two fans are used.

5.3.2. Deduction Method

The deduction method consists on varying the pressure p_m in the **pressure ring**, keeping a constant pressure, p_r, in the **room** as schematized in Figure 5.2 so that :

$$p_r - p_m = \Delta p \tag{5.7}$$

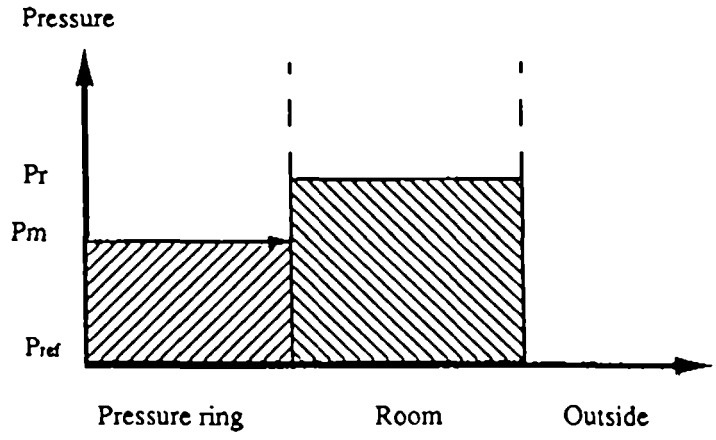


Figure 5.2: Pressure level in pressurization test with deduction method.

By using this method it is possible to measure all the flows directly or indirectly, as described in more detail in Appendix 4, Section 2.

5.3.3. Guard Zone Technique

In this technique, the pressure in the **pressure ring** (guard zone) is always the same as that of the **room** (guarded zone) as illustrated in Figure 5.3.

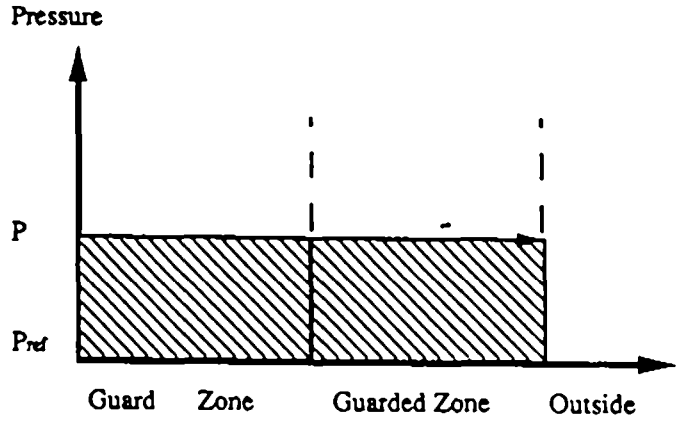


Figure 5.3: Pressure levels in pressurization test with guard zone method.

By using this method it is also possible to measure all the flows directly or indirectly, as described in much detail in Appendix 4, Section 3. In most cases, the guard zone technique leads to smaller errors than the deduction technique *[Fürbringer and Roulet, 1991]*.

5.4. Obtaining the Leakage Coefficients

The leakage coefficients, C and n or a, b and c, are obtained by fitting the measured results, $Q(\Delta p)$, to the equations (5.1) or (5.2), which are repeated here, in terms of mass air flow rates:

$$Q = C\,\Delta p^n \qquad \text{(5.1 again)}$$

or:

$$\Delta p = a\,Q^2 + b\,Q + c \qquad \text{(5.2 again)}$$

Depending on the number of measured points (or measured pairs Q, Δp), various methods can be used.

5.4.1. Two Measured Points

If (and only if) there is an absolute confidence in one of these models, that is if the purpose of the test is to obtain the most accurate values of the parameters in equation (5.1) or (5.2) and **not** to verify if these models fit well on the measurements, the best experimental plan† is to measure the air flow rates, $Q(\Delta p)$, at only two extreme pressures: the lowest and the highest possible pressures compatible with the instruments and the measured building *[Fürbringer, Roecker, Roulet, 1988]*. These measurements will give two pairs of results: Q_1, Δp_1 and Q_2, Δp_2. The coefficients are then obtained by solving a pair of equations (5.1) or (5.2), which gives:

to evaluate C and n

$$n = \frac{\ln(Q_1/Q_2)}{\ln(\Delta p_1/\Delta p_2)} \qquad (5.8)$$

$$C = Q_1\,(\Delta p_1)^{-n} = Q_2\,(\Delta p_2)^{-n} \qquad (5.9)$$

† Here, the "best plan" is the plan giving finally the most accurate results with a minimum amount of work.

and to determine a and b, (with c assumed to be 0):

$$a = \frac{\Delta p_1 Q_2 - \Delta p_2 Q_1}{Q_1 Q_2 (Q_1 - Q_2)} \tag{5.10}$$

$$b = \frac{\Delta p_1 Q_2^2 - \Delta p_2 Q_1^2}{Q_1 Q_2 (Q_2 - Q_1)} \tag{5.11}$$

If there is a pressure difference, Δp_0, with no air flow (ie. the fan is off and its aperture closed), Δp_0 can be measured and deduced to the two other measurements to obtain Δp_1 and Δp_2. In this case, c = Δp_0 and the coefficients, a and b are given by equations (5.10) and (5.11). The measurement of the pressure difference at no air flow is in fact a third measurement point.

The error, $\delta y = T(P,\nu)\ s(x_i)$, on the results, $y = y(x_1, ...,x_i,...)$, can be deduced from the standard deviations of the measurements $s(x_i)$ using equation A 2.21 of Appendix 2.

As an example, let us apply this equation to the formulas (5.1) and (5.2). Calculating $\partial n/\partial Q$ and $\partial n/\partial \Delta p$, we find finally:

$$s^2(n) = n^2 \sum_{i=1}^{2} \frac{s^2(Q_i)}{Q_i^2 \ln^2(Q_1/Q_2)} + \frac{s^2(\Delta p_i)}{\Delta p_i^2 \ln^2(\Delta p_1/\Delta p_2)} - \frac{s^2(Q_i,\Delta p_i)}{Q_i \ln(Q_1/Q_2)\, \Delta p_i \ln(\Delta p_1/\Delta p_2)} \tag{5.12}$$

and for C, assuming that Q_1 and Δp_1 are used:

$$s^2(C) = C^2 \left(1 - \frac{\ln(\Delta p_1)}{\ln(\Delta p_1/\Delta p_2)}\right)\left(\frac{s^2(Q_1)}{Q_1^2} + \frac{n\, s^2(\Delta p_1)}{\Delta p_1^2} - \frac{n\, s^2(Q_1,\Delta p_1)}{Q_1\, \Delta p_1}\right) + C^2 \frac{\ln(\Delta p_1)}{\ln(\Delta p_1/\Delta p_2)}\left(\frac{n\, s^2(Q_2)}{Q_2^2} + \frac{s^2(\Delta p_2)}{\Delta p_2^2} - \frac{n\, s^2(Q_2,\Delta p_2)}{Q_2\, \Delta p_2}\right) \tag{5.13}$$

To obtain the results above, it was assumed that the two measurements are not correlated, that is:

$$s^2(Q_i,\Delta p_j) = s^2(Q_i,Q_j) = s^2(\Delta p_i,\Delta p_j) = 0 \text{ if } i \neq j \tag{5.14}$$

5.4.2. Least Square Fit or Other Identification Methods

If the air flows are measured for more than two points (e.g. to check if the models really fits), an identification method should be used to obtain the coefficients. The most common way is first to linearize the equations (5.1) or (5.9):

for equation 1, taking the logarithm of both sides:

$$\ln Q = \ln C + n \ln(\Delta p) \tag{5.15}$$

which can be written as a linear relationship:

$$y = a + n\, x \tag{5.16}$$

with:

$$\begin{aligned} y &= \ln Q \\ a &= \ln C \\ x &= \ln(\Delta p) \end{aligned} \tag{5.17}$$

Equation (5.2) can be rewritten, dividing by Q:

$$\frac{\Delta p - \Delta p_0}{Q} = a\, Q + b \tag{5.18}$$

That is again

$$y = a + b\, x \tag{5.19}$$

with:

$$y = \Delta p/Q \qquad \text{and} \qquad x = Q \tag{5.20}$$

Then, one of the methods given in Appendix 3 can be used to identify the parameters, a and b, and the corresponding confidence intervals.

Finally, from a and b, it is easy to come back to the original coefficients:

if the equation (5.1) is used:

$$C = \exp(a) \qquad \text{and} \qquad n = b \tag{5.21}$$

and a and b are the coefficients sought if equation (5.2) is used.

Note that a multilinear least square fit can also be used to get the three coefficients, a, b and c, of equation (5.2) from more than three measurements.

5.5. Corrections For Standard Conditions

If different measurements should be compared, which are not done under the same atmospheric conditions, it may be useful to correct the coefficients in order to reduce them to standard conditions, that is for example 20 °C and 0.1013 MPa.

Let use the indice o for these standard conditions and no indice for the measurement conditions. Then:

$$C_o = C\,(\mu/\mu_o)^{(2n-1)}\,(\rho/\rho_o)^{(1-n)} \tag{5.22}$$

where μ is the viscosity [kg $s^{-1}m^{-1}$] and ρ the density of air. The variations of the air density will be, from equation (5.4):

$$\frac{\rho}{\rho_o} = \frac{p\,T_o}{p_o\,T} \tag{5.23}$$

and the variation of the viscosity is given by the following approximation in function of the absolute temperature, T:

$$\mu = \frac{1{,}458.10^{-6}\sqrt{T}}{1 + 110{,}4/T} \tag{5.24}$$

hence:

$$\frac{\mu}{\mu_o} = \sqrt{\frac{T}{T_o}}\;\frac{1 + 110{,}4/T_o}{1 + 110{,}4/T} \approx \frac{17{,}1 + 0{,}047\,\theta}{17{,}1 + 0{,}047\,\theta_o} \tag{5.25}$$

where θ is the temperature in degree Celsius. The approximation given in the second part of the formula (5.25) can be used between -10 °C and 40 °C.

Since the correction is small and if the temperatures and pressures are known with a reasonable accuracy, the additional errors introduced by this correction is negligible.

5.6. Leakage Area

The equivalent leakage area of each building element may be calculated from the leakage parameters as follows, for a given, conventional pressure difference:

$$A_L = C_o\,(\rho/2)^{1/2}\,\Delta p^{(n-1/2)} \tag{5.26}$$

This is the area of a sharp edge orifice having a discharge coefficient equal to 1 and the same leakage at pressure, Δp, as the measured element. The usual conventional pressure difference is 4 Pa *[ASTM, E-779-87]*.

The standard deviation of the leakage area is computed by:

$$s^2(A_L) = A_L^2\,[(s(C_o)/C_o)^2 + (s(n)\,\ln(\Delta p))^2] \tag{5.27}$$

6. Equipment

This chapter deals with the practical matters of the equipment to be used for performing whole building pressurization measurements as well as air leakage path determination. The requirements with respect to the appropriate range of air flow rates to be delivered by the equipment as well as to the pressure and air flow rate metering devices are discussed in general terms. A calibration chamber for complete pressurization equipment is presented. Finally a number of commercially available blower doors and other related equipment for air tightness measurement and air leakage detection are compared.

6.1. Requirements

6.1.1. General Requirements

The fundamental requirements of a fan-pressurization system are simple: it must be capable of blowing air into, or out of, a building so as to cause a difference in pressure between inside and outside. The rate at which the air is blown in or out must be measured as well as the magnitude of the pressure difference between inside and outside. In addition, the system must be capable of adjusting the air flow rate over a wide range.

Clearly the equipment also needs to be simple to set up and portable so that it can be moved easily between buildings to be tested, and rugged enough to withstand the inevitable knocks which occur when it is transported. The latter applies particularly to the instruments used for air flow and pressure measurements. Much more difficult to describe is the required equipment performance because this depends on the size and airtightness of the buildings to be examined.

6.1.2. Dwellings

The air leakage rates of dwellings varies from one country to another because of differences in the materials used in construction, the types of construction used and the attention given to the construction process (such as jointing of vapor barriers, sealing around window frames, etc.). Differences in the size (volume or surface area) of dwellings most commonly found in different countries will also influence the required performance.

Fortunately, a convention of measuring air leakage at pressure differences up to 50 Pa has gained international acceptance *[e.g. ISO 9972, 1991]*, so that only the fan pressurization system air flow capacity need to be considered further. Note that if an industrial ventilating fan is to be used for a 'home made' fan pressurization system, the fan air flow capacity quoted by the manufacturer may not be realized in some cases because of the flow resistance of the air flow measuring device, other obstructions (e.g. an anti swirl device) and the absence of the ducts which were used when the manufacturer tested his fan.

The air flow rate required in a pressurization test was stated in an early Swedish Standard *[SS 02 15 51, 1980]* as between 1 000 and 3 000 m^3/h but this guidance is not given in later editions *[SS 02 15 51, 1987]*. The ASTM standard in the United States suggests air flow rates up to 1.4 m^3/s (or 5 040 m^3/h) *[ASTM E 779-87]*. In the UK a capacity of 4 000 m^3/h is usually sufficient but may be inadequate in dwellings with 4 or more bedrooms. In all cases this air flow rate should be achievable at a building envelope pressure difference of at least 50 Pascals.

6.1.3. Large Buildings

In larger buildings, such as warehouses, schools and office blocks, the specification of required equipment performance is more difficult, often because of the small number of air leakage measurements which have been carried out in these types of buildings and the range of physical sizes of buildings which are encountered. Some air leakage measurements in large buildings (both offices and single cell buildings) including measurements made in Canada, Sweden, UK and USA have been reported and reviewed *[Perera and Tull, 1989; Perera, Stephen and Tull, 1989]*. One of the striking observations here was the range of building volumes which were tested; ie. office buildings from 5 300 m^3 to a staggering 246 000 m^3 and single cell buildings from 3 000 to 61 000 m^3 (In the USA the office buildings were usually pressurized by means of the building's own air handling plant, thus eliminating the need for very large portable pressurization equipment, however this approach is not possible in naturally ventilated buildings). Furthermore the air leakage rates varied widely at between 2.0 and 12 $m^3/hr/m^2$ of envelope surface area at 25 Pascals pressure difference in offices and up to 45 $m^3/hr/m^2$ at 25 Pascals in UK single cell buildings (Swedish single cell building leakage rates were similar to those of office buildings).

Clearly it is difficult to specify the fan-pressurization system capacity required for a large building on the basis of building characteristics. In practice, the system capacity is more likely to be determined by physical limitations such as what size of fan it is practical to move from site to site and connect to the building to be tested or what is the available electrical power supply. One portable fan pressurization system for large buildings used a 2 meter diameter axial fan powered by a road trailer mounted diesel generator giving an air flow rate of about 22 m^3/s *[Tamura and Shaw, 1978]*.

Another approach which has met with some success in the UK *[Perera, Stephen and Tull, 1989]* was to use up to three separate fan-pressurization systems, each powered from an ordinary electrical wall socket outlet and giving an air flow rate of about 5.5 m^3/s from each system. This also allows the equipment to be matched to the airtightness of the building by using only that number of systems required to achieve the desired pressure difference.

6.1.4. Envelope Pressure Measurement

The pressure difference between inside and outside the building being tested must be measured using some kind of mechanical pressure gauge, electronic transducer or liquid filled manometer (see Section 3.1). The particular type of instrument used is of little consequence but the following points should be considered.

The pressure differences to be measured are generally in the range 5 to 60 Pascals (although higher pressures may be required in particular circumstances). High accuracy laboratory type instruments are not appropriate for measuring such pressures in the field and so the accuracy of the portable instruments required is not likely to be much better than ± 2 Pascals. The scale interval used on the instrument should ideally not be greater than 1 Pascal, and certainly no greater than 2.5 Pascals.

The envelope pressure difference will not be absolutely constant because of the effects of wind and, perhaps, turbulence of the air flow through the pressurization fan system. Thus, it is desirable to incorporate some form of damping on those instruments which have a very fast response, such as electronic micromanometers with diaphragms. Liquid filled and mechanical devices usually have sufficient damping inherent in their design.

6.1.5. Air Flow Rate Measurement

A complete description of air flow measuring instruments is presented in Section 3.2. Below are presented the advantages and disadvantages of some of these instruments or techniques, when used in a pressurization system.

The use of primary flow measurement devices in accordance with national and international standards (e.g. orifice plates) would eliminate the need for calibration of complete equipment, apart from the pressure measuring instruments of course. However, in practice, this generally requires long lengths of straight ducting which hamper portability and can be difficult to use in some building layouts because of the presence of obstructions. The exceptions here, in small sizes at least, are inlet devices which can be successfully used in accordance with standards. The majority of pressurization fans therefore use non standard flow measurement methods and the complete system has to be calibrated for air flow rate before use.

The air flow rate through the pressurization fan may be measured in a number of different ways, such as by using "fan characteristic" curves, a vane anemometer in the fan duct, tracer gas dilution, orifice plates, conical/Borda inlets, Venturi tubes, Pitot (static) tubes/rakes or proprietary air flow measurement devices.

A "fan characteristic" is essentially a family of curves on a graph relating the air flow rate to rotational speed of the fan impeller and the pressure difference against which it is working. The method was used extensively in early designs of "blower door" in North America but has since fallen from favour because of the continual need for recalibration and sensitivity to very small changes in blade position, clearance, obstruction and shape *[Retrotec, 1985]*.

The vane anemometer has been successfully used in at least one design of pressurization fan and has not suffered significant deviation from calibration over periods of a year or more. Note that the complete system should be calibrated at several pressure differences to relate the vane anemometer readout to total air flow rate.

The tracer gas dilution method consists simply of the constant injection of a tracer gas into the pressurization fan air flow with good mixing. Measurement of the concentration of tracer gas at the downstream end of the fan duct allows the air flow rate to be calculated. The method has been used frequently for air leakage testing of large buildings and is universal if the building's own mechanical ventilation system is being used to effect the pressurization. This is because of the relative difficulty of

making reliable air flow measuring devices in the large sizes needed for such situations and the impracticality of fitting them in existing duct systems in buildings.

The main problem with the method is the long length of duct required to ensure adequate mixing of tracer gas with the air flow, or the resistance to air flow of devices inserted into the fan duct to encourage good mixing.

Pitot tubes, Pitot static tubes and rakes (arrays of interconnected tubes) have been used for air flow measurement but are not popular. Their main disadvantage is that the magnitude of the pressure difference from such tubes (1 x velocity pressure) is usually quite small and therefore difficult to measure at the lower air flow rates. It is not easy to introduce devices in the fan duct to increase the magnitude of the pressure difference at low flow rates (compare with orifice plates below).

Conical inlets, nozzles, Borda mouthpieces and Venturi tubes are examples of devices which all use the reduction in static pressure generated by accelerating an air flow into, or within, a duct as an indicator of air flow rate. The pressure differences generated by these devices can be far greater than those obtained with Pitot tubes in plain ducts so low air flow rates are less of a problem, but given the limitations on fan capacity imposed by portability and power consumption, it will usually be necessary to have a number of interchangeable devices of different diameters to cover the range of air flow rates required. Nonetheless, these are very practical air flow measurement devices for use on pressurization equipment and have been used successfully on commercially made systems

Orifice plates are the most commonly used air flow measurement devices on pressurization fan systems. Whilst they cannot be used as primary flow measurement devices as described in various national and international standards *[BS 1042, 1981], [ISO 5167, 1980]*, careful calibration allows their use, combining simplicity with convenience and reliability. In most systems the largest orifice plate is simply the relatively sharp edged pressurization fan intake casing. For lower air flow rates a restrictor plate is fitted over this main orifice thereby increasing the pressure difference across the orifice plate for a given air flow rate. The restrictor plate may contain not one but several orifices which can be progressively closed off to further extend the air flow measurement range of the equipment. (NB: Several commercially made pressurization fan systems have used an inlet nozzle for the highest air flow rates with a multi-orifice restrictor plate fitted over the nozzle for the lower air flow rates).

There are various proprietary air flow measurement devices available which could be used on pressurization equipment. Most of these will also require calibration of the complete equipment.

6.1.6. Door (or Window) Module

The other main component of a pressurization fan system is the replacement door (or window) module which allows the pressurization fan to be sealed into an open doorway, or sometimes an open window, in the building to be tested. Although single panels (e.g. plywood) cut to fit the opening and sealed in place with adhesive tape can be used, it is much more convenient if a special assembly is made which can be adjusted in height and width to fit a wide variety of door and window sizes. Clearly this should be designed in such a way as to make a reasonably airtight seal all round its perimeter (even in openings which are not quite square and true) and should not leak significantly itself (e.g. where flat components slide over each other as part of the method of adjustment). Note that a gap of 0.2 mm all round a typical door size represents a hole of about 11 cm^2, which is significant.

It is worth noting that door sizes vary from one country to another. Therefore it is important to ensure in advance that commercially supplied blower doors will fit the intended openings.

6.2. Calibration

6.2.1. Need for Calibration

Any equipment which is used in the field will inevitably suffer from being transported from place to place and frequent assembly and disassembly. There may even be cases of abuse by the operators! Regular calibration of the more vulnerable components is required and in some cases the complete system requires regular calibration.

6.2.2. Pressure Measuring Instruments

There are already recognized methods of calibrating pressure measuring instruments, e.g. comparing them with a reference instrument in a laboratory such as a Betz-type water column manometer, so

little needs to be said about this here. The more delicate the instrument the more frequently it should be calibrated. The Canadian Standard for Fan Testing Contractors requires inclined manometers (i.e. liquid filled inclined tube manometers) to be calibrated initially, and whenever they are damaged or modified *[CAN/CGSB-149.10-M86, 1986]*; pressure gauges, pressure transducers and associated electronics must be calibrated so it seems sensible to calibrate them annually as is required for the other types of instrument.

On equipment which includes more than one pressure measuring instrument it is easy to make a quick check on their operation immediately before use by connecting the instruments together, applying a pressure to them and checking that they all read the same. Clearly this can only be done if the measurement ranges of the instruments overlap.

6.2.3. Air Flow Calibration of Complete Systems

There are, no doubt, a number of ways of calibrating fan pressurization equipment but the most obvious are perhaps velocity traversing of the fan duct and depressurizing an airtight chamber fitted with primary air flow measuring devices.

Making a velocity traverse of the fan duct using a Pitot static tube is quite possible and can be reasonably accurate (say, better than ± 5 %) but it does take a few minutes to complete a single traverse during which time the fan speed tends to vary. This method is therefore not recommended.

The ideal way to calibrate a fan pressurization system is to fit it, including the door module, into the end of an airtight chamber such as that shown in Figure 6.1 which measures 2 meters by 2 meters by 4 meters (internally). The pressurization fan depressurizes the chamber and air is admitted to the chamber only via an air flow measuring device at the opposite end. The air flow rate through both the flow measuring device and the pressurization fan system is therefore the same. Different sized flow measurement devices allow calibration over different flow rate ranges and pressure differences.

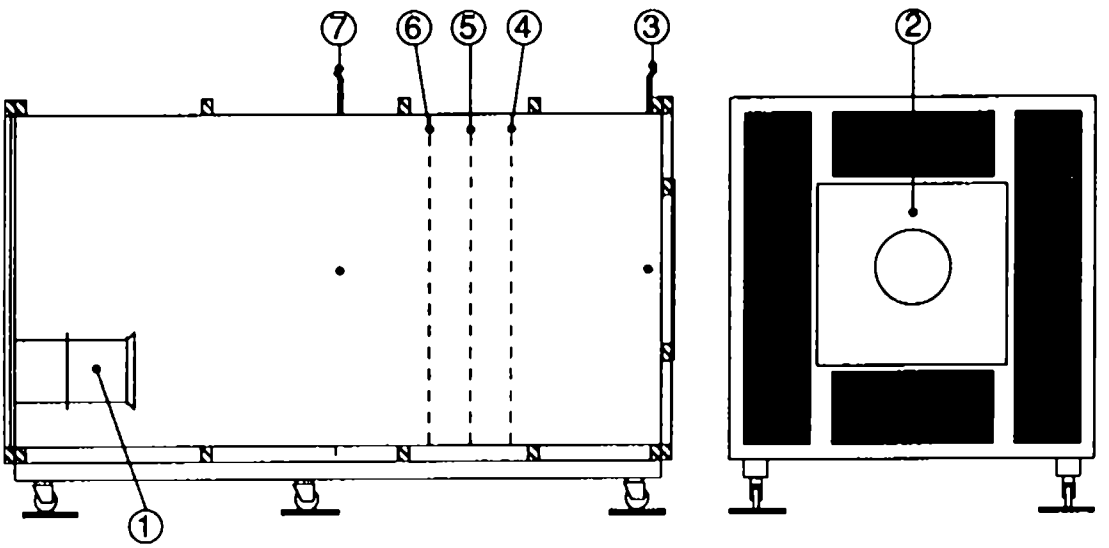


Figure 6.1.: Pressurization fan calibration chamber (BRE, UK). Sectional side view and orifice mounting.

Figure 6.1 shows a chamber designed at BRE (UK) based on guidance given in *[BS 848, 1980]*. There are four points of detail in which the design illustrated departs from the precise guidelines of the standard, largely because of the limited space available when it was designed. These are:

(1) The Standard calls for an inlet orifice to be mounted on the upstream end of a length of cylindrical ducting which is itself mounted on the upstream end of the chamber. For orifices up to 800 mm diameter this duct would have to be at least 1 meter in diameter by 3 meters long. This would have made the whole assembly to big for the indoor space available at the time so a

compromise was made whereby the orifice plate was mounted directly on the end of the chamber. The chamber itself therefore takes the place of the cylindrical duct. *[BS 1042, 1984]* does however cover the use of orifice plates with no upstream and/or downstream duct.

(2) The screens inside the chamber, which are intended to break up the jet of air entering the chamber and prevent it impinging on the equipment under test, may not be too close to the orifice although the standards are not clear on this. Because the screens are very porous their effect on the flow through the orifice is assumed to be insignificant.

(3) When the larger sized orifice plates are used the chamber is not large enough to be considered a large space and so must be considered to be a downstream duct. The downstream duct should strictly speaking have a circular cross section, not square as in Figure 6.1, but this is thought to be of little consequence because the orifice plates are mounted symmetrically on the chamber center line and are small in area compared with the chamber cross section.

(4) References *[BS 848, 1980]* and *[BS 1042, 1984]* state that there should be no wall closer than four orifice diameters to the axis of the orifice or to the plane of the upstream face of the orifice. The maximum orifice diameter required was 810 mm which, to conform with this requirement, would require the chamber to be raised over 2 meters off the floor. This was unacceptable so tests were made to investigate the effect of putting a single wall close to an inlet orifice. These tests indicated that the effect could reasonably be ignored in this case.

A number of orifice plates were used up to 810 mm diameter. However, according to references *[BS 848, 1980]* and *[BS 1042, 1984]*, there are limitations on the use of these below certain pressure differences due to rapidly changing orifice flow coefficients at Reynolds numbers below 50 000. This implies that, for normal atmospheric conditions, the orifice plate pressure difference (in Pascals) should not be less than $(1\,000/d)^2$ where d is the orifice diameter in millimeters. This affects the smaller orifice plates less than about 500 mm diameter; e.g. a 100 mm diameter orifice should be used only down to a pressure difference of 100 Pascals. However, the Reynolds number effect is far less pronounced for orifice plates between large spaces than for those mounted as inlet or outlet devices on ducts. Reference *[BS 1042, 1964]* indicates that orifice plates can be used under these circumstances at lower Reynolds numbers and reference *[BS 1042, 1984]* allows use of orifice plates greater than 50 mm down to a Reynolds number of 20 000. The orifice pressure difference is then limited to not less than $(400/d)^2$ where d is in millimeters; e.g. a 100 mm diameter orifice plate may be used down to 16 Pascals pressure difference.

According to *[Ower and Pankhurst, 1977]* the flow coefficient of orifice plates between large spaces rises from 0.596 at Reynolds number of 100 000 to a value of 0.600 at 20 000 with uncertainty of ± 0.5 %. Reference *[BS 1042, 1964]* states that the flow coefficient for inlet orifices is 0.60 for all sizes up to 0.810 meters diameter mounted on a 2 meter diameter duct but with uncertainty of ± 1.5 % and Reynolds number greater than 50 000. For the purpose of calibrating pressurization fan equipment it is reasonable to use a value of 0.60 for all calculations of air flow rate. The overall air flow measurement uncertainty may be expected to be better than ± 2.5 %.

Similar testing procedures are outlined in *[ASTM E 1258-88]*, which applies to the system of measuring air leakage as described in *[ASTM E 779-87]*. Two basic calibration procedures are presented, the preferred one being based on [ASHRAE 51/AMCA 210].

6.3. Available Equipment: Blower Doors

6.3.1. Commercial DC Pressurization Equipment

Measurements of building envelope airtightness can be performed by using a fan which is temporarily installed in the building envelope. This type of equipment was initially developed as a research tool. Versions of this type of equipment are now available from several commercial organizations. This equipment is often known as a Blower Door. A list of manufacturers of such equipment is given in table 6.1. Most doors are designed to cope with domestic situations although at least one manufacturer produces a multi-fan door which finds application in light industrial buildings and commercial premises.

6.3.2. Blower Door Design

Blower door design varies from manufacturer to manufacturer but essentially each door comprises a variable flow rate fan and some means of holding the fan in place in an existing door frame.

Air Quality Labs, Inc.
Vista Industrial Park
Building 5
Spokane, WA 99 206
USA
Tel: (509) 325-4281

Eder Energy
7535 Halstead Dr.
Mound, MN 55 364
USA
Tel: (612) 446-1559

The Energy Conservatory
920 West 53rd Street
Minneapolis, MN 55 419
USA
Tel: (612) 827-1117

Your Energy Service
2204 Elliston, Suite F
Nashville, TN 37 203
USA
Tel: (615) 329-9747

Infiltec
5597 Seminary Road
Suite 2412 South, PO Box 1533
Falls Church, VA 22041
USA
Tel: (703) 820-7696

Retrotec
PO Box 5632, Station F
Ottawa, ONT
Canada K2C - 3M1
Tel: (613) 723-2453

Mekankonsult Lifa
Gökvägen 13
S-35 242 Växjö
Sweden Tel: (470) 22 956

Elmicro
Box 22
S-360 50 Lessebo
Sweden
Tel: (478) 11 376

Table 6.1.: Several Blower Door Manufacturers

Two door frame systems are in general use. In the first, rigid modular panels are used to fill the door frame. These panels are fitted with sliding extension pieces which can be locked in place once the panel has been expanded to the size of the door frame. One panel contains the fan and the modular approach is used to ease transportation of the equipment from one site to another. A modular panel blower door is shown in Figure 6.2.

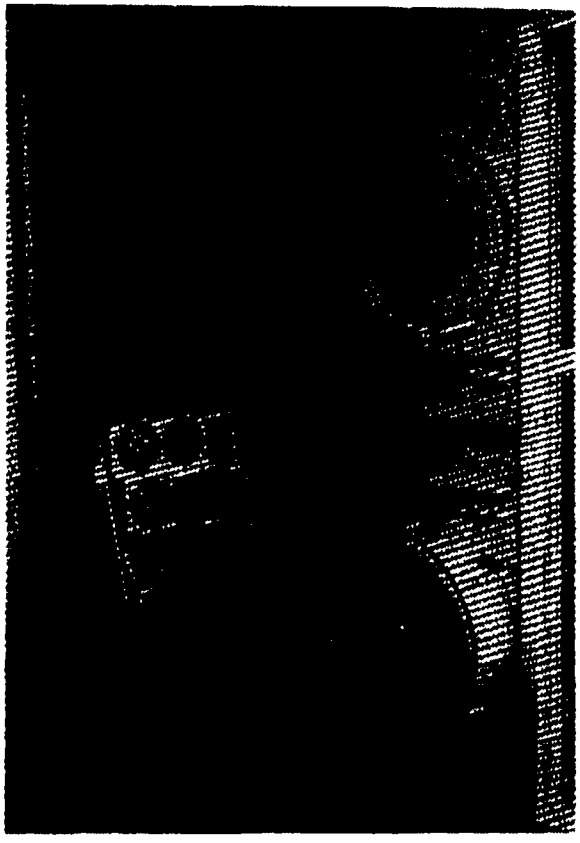


Figure 6.2.: Blower door. Modular panel type. Retrotec (see Table 6.1)

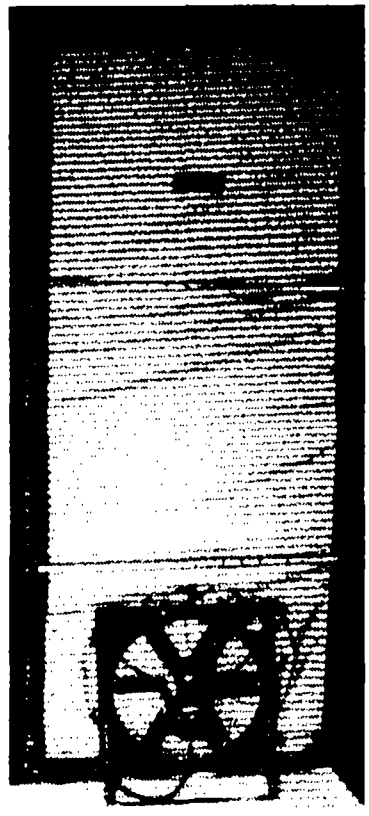


Figure 6.3.: Blower door. Expanding frame type. Eder Energy (see Table 6.1).

A second method uses a metal frame which can be expanded to match the dimensions of the door frame. This is then covered with a strong nylon or polythene fabric thus providing the required seal. The fan then rests on the floor and penetrates the fabric through a tightly fitting opening. This type of door is illustrated in Figure 6.3.

The major working component of the blower door is the fan. This must be powerful enough to create the range of volumetric flow rates required for the test. The flow rate required will depend upon the volume of the building and its airtightness at the pressure differentials reached. In order to facilitate pressurization and evacuation measurements, the flow should ideally be reversible. This can be achieved physically, i.e. turning the fan around, or electrically, i.e. reversing the rotation of the blades. Some door fans are powered by direct drive DC motors and others by variable speed AC motors.

Several door fans are produced which are uncalibrated in terms of air flow rate. These instruments may only be used for the qualitative location and assessment of air leakage sites. However, most doors are calibrated thus enabling the air flow through the fan to be evaluated. Direct flow measurement techniques are based on the relationship between the air flow rate through a nozzle or orifice and the pressure drop across such a constriction. This is a well understood technique (see, for example *[Ower and Pankhurst, 1977]*), and in practice would involve, for example, measuring the static pressure drop across the fan inlet. The flow rate is then evaluated from this pressure drop using an equation derived from calibration data. The restriction required to produce the pressure drop may decrease the flow capacity of the fan.

A second technique employed involves calibrating the flow rate in terms of the fan speed and the internal/external pressure difference (see, for example, *[Persily, 1984]*). The air flow rate is given by the general function:

$$Q_F = f(\omega, \Delta p) \tag{6.1}$$

Where:

Q_F is the air flow rate through fan, [m^3s^{-1}]

ω is the fan speed, [s^{-1}]

Δp is the pressure differential across the fan, [Pa]

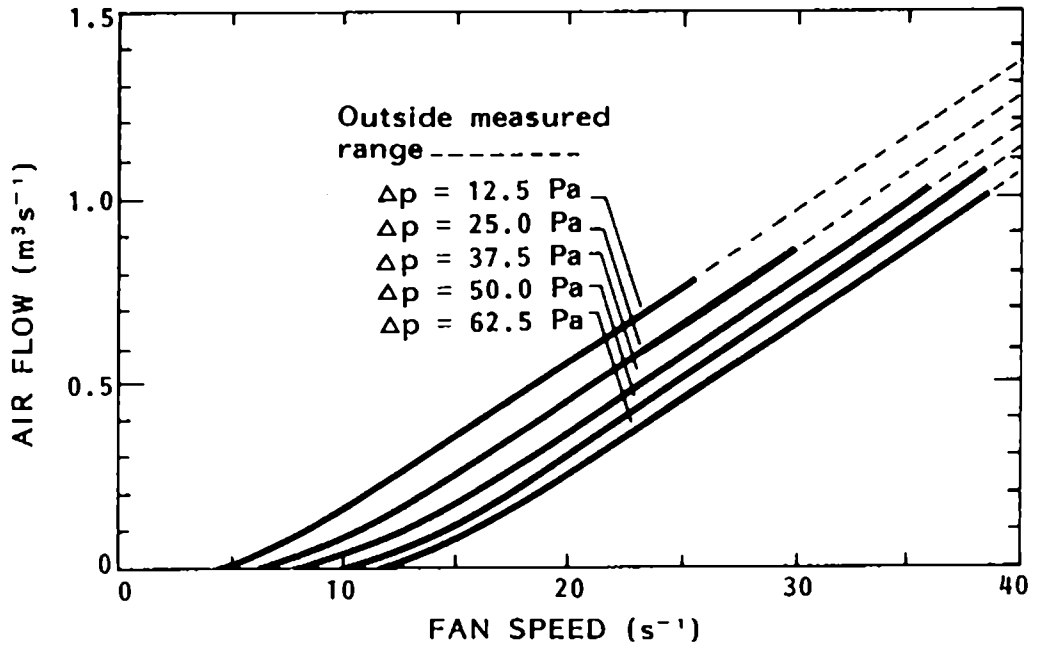


***Figure 6.4.:** Example calibration curves for blower door equipment. See equation 6.1 [Persily, 1984]*

The relationship between the above parameters can be derived by using the blower door to pressurize a calibration chamber. The air flow rate out of the chamber is measured together with the fan speed and the chamber pressure differential. A family of curves is derived (see Figure 6.4) and the air flow rate is obtained on site from measurements of fan speed, using a tachometer, and inside/outside pressure difference. Hence the output from a blower door will minimally consist of pressure and/or fan speed readings.

Several companies can also supply a variety of computer hardware and software. This allows the tests to be performed with greater ease and accuracy and enables estimates of parameters such as air change rate or equivalent leakage area to be obtained directly.

These packages range from the manual analysis of the raw data with a hand-held computer or calculator, through automatic analysis by computers which are hooked up directly to the blower door, to sophisticated systems which will automatically run a series of tests at incremental pressure differences then provide digital read-outs, printed graphs and diagnostic data.

In general, the more sophisticated the equipment the more expensive it will be and the analysis package often represents a significant proportion of the total cost of the blower door system.

6.3.3. Comparison of Several Blower Doors

As indicated in Section 6.3.2. commercial blower doors vary in design, sophistication and cost. Actual costs of blower doors will alter both with time and currency exchange rates so no indication of cost is given here. For current price information, individual manufacturers should be contacted - see Table 6.1.

Manufacturer and model	Flow Rate Type	Opening Size [m] min	Opening Size [m] max	Weight [kg] all	Weight [kg] fan	Flow Rate Range [m^3s^{-1}]	Quoted Accuracy %	Motor Type AC/DC
Air Quality Labs:								
CARE door	T	0.74×1.98	0.94×2.18	39	18	0.00-3.49	5	DC
CAP door	T	0.74×1.98	0.94×2.18	23	18	0.00-3.49	5	DC
Eder Energy SA-1	NA	0.61×1.83	0.94×2.23	15	11	0.00-1.23	Non Cal.	AC
Eder Energy CA-2	P	0.61×1.83	0.94×2.13	19	15	0.00-1.65	5	AC
Eder Energy CA-3	P	0.61×1.83	0.94×2.13	20	16	0.00-2.12	5	AC
Energy Conservatory Minneapolis door	P	0.61×1.22	1.02×2.39	23	15	0.02-2.83	5	AC
Infiltec R-1	P	0.71×1.98	0.91×2.23	34	18	0.25-2.24	5	AC
Infiltec E-1	NA	0.71×1.98	0.91×2.23	36	18	0.00-1.60	Non Cal.	AC
Infiltec E-2	NA	0.71×1.98	0.91×2.23	38	18	0.23-1.60	Semi Cal.	AC
Mekankonsult Lifa blower door	P	–	0.88×2.08	18	8	0.02-0.84	5	AC
Retrotec 710	P	0.76×1.92	0.96×2.19	48	17	0.01-2.78	5	AC
Retrotec 720	P	0.76×1.92	0.96×2.19	49	17	0.01-2.26	5	AC
Retrotec 650	P	See manuf.	See manuf.	69	53	0.00-6.37	5	AC
Your Energy Service	P	0.76×1.93	1.22×2.13	41	32	0.00-4.01	Non Cal.	AC

Table 6.2.: Specifications of a selection of blower doors

Table 6.2. presents the relevant characteristics of several commercially available blower doors. The parameters examined are:

Flow rate type. This indicates the method by which the flow rate through the fan is measured.

P = Pressure Device

T = Tachometer (Fan Speed)

NA = Not applicable

An explanation of the above two methods is given earlier in Section. 6.3.2.

Opening size. This gives the maximum and minimum opening size into which the door panel can be fitted. Some door frames may be too large for the panel to fill, but this may be overcome with an improvised seal. However, if the panel is too large for a given door frame then this may be a more difficult problem to resolve.

Weight. The weight of all the equipment and the fan alone is given. This can be an important factor if the blower door equipment has to be frequently transported from one measurement site to another.

Flow rate change. This is the flow rate range of the fan, usually when operating against a back pressure of 50 Pa. It is essential for the fan to be able to meet the flow rate requirements of the test. In general the larger and more leaky the building under test the greater the required flow rate capacity.

Quoted accuracy. This is the manufacturer's quoted accuracy for the rate of air flow through the fan. Often, especially if the blower door is to be used for research purposes, individual operatives will recalibrate the blower door during the course of its working life.

Motor type. This indicates whether the motor of the fan operates on Direct or Alternating Current.

The information presented in Table 6.2. was gathered from individual manufacturers or adapted, with permission, from an article which originally appeared in "Energy Auditor and Retrofitter", which is a magazine dealing with home energy conservation and is produced in Berkeley California (Tel.: (415) 524-5405).

6.3.4. AC Pressurization System

The AC pressurization system as described 4.1.3. is commercially available. For further information contact:

David Saum, Infiltec
5597 Seminary Road, Suite 2412 South.
PO Box 1533
Falls Church
Virginia 22041
USA
Tel.: +1 703 - 820 - 7696

For specific technical and research information contact:

Mark Modera
Lawrence Berkeley Laboratory
University of California
Berkeley
CA 94720 USA
Tel.: +1 415 - 486 - 4022

6.4. Available Equipment: Pressurization Fans

6.4.1. Application

Blower doors are very well suited for whole building pressurization. However, for many methods as described in Section 4, where interzonal leakage determination is requested, or in general, where smaller air flow rates are to be measured, small size fans are to be applied. At the other end of the scale, for large volume buildings, huge fan systems are required.

This subsection describes a few of these pressurization fan systems, without being complete in the listing of commercially available systems.

6.4.1. Compensated Flow Meter

The Flow Finder has been developed for the method described in Section 4.3.5. It is a portable instrument (3.7 kg) which is used to measure the air flow rate through openings such as cracks, grilles etc. by the pressure compensation method. The pressure drop through the instrument is compensated by adjusting manually the speed of a fan.

The measured air flow rate ranges from 0 to 0.063 m^3/s (0 to 225 m^3/h), the accuracy being 5 % of reading ± 0.0005 m^3/s (± 2 m^3/h). The resolution of the zero pressure indicator is ± 1 Pa. A standard adaptor cone is provided to allow the measurements of flow rates through openings as wide as 425 × 340 mm. Other adaptors can be mounted.

This instrument can be obtained from:

Instrumentbedrijf ACIN BV — Tel. + 31 70 88 8990
Postbus 19191, NL-2500 CD den Haag — Telex 33214

6.4.3. Lower Range Pressurization Fans

A commonly used equipment for the lower air flow rate range of pressurization applications is the Fläkt-system ABBA-700. It is designed for quick and accurate measurement of leakage, e.g. in ducting, chimney stacks, of components, of smaller volume envelopes, etc. It can be used in combination with a blower door or another fan in the multifan methods (4.3.3., 4.3.4.) or as basic air flow measuring system, as in the methods 4.3.5. and 4.3.6. The air flow rates range from 0.8 dm^3/s (3 m^3/hr) to 200 dm^3/s (750 m^3/hr) for a pressure difference from 5 to 100 Pa. (For pressure testing in ducting a maximum static pressure of 1800 Pa, with an air flow rate of 19 dm^3/s, is possible).

The equipment consists of:

- a fan with variable voltage transformer for continuously variable control of the speed and air flow;
- 3 measuring tubes with orifice plates of
  25 mm diameter for the flow range of 0.8 to 15 dm3/s (3 to 55 m^3/hr)
  50 mm diameter for the flow range of 5 to 50 dm3/s (20 to 200 m^3/hr)
  100 mm diameter for the flow range of 20 to 200 dm3/s (70 to 700 m^3/hr)
- 2 U-tube manometers for measuring the static test pressure and the flow through the measuring tube,
- a hose for connection to the measurement object,
- a storage case for easy transporting, weighing approx. 30 kg.

6.4.4. Higher Range Pressurization Fans

To determine the envelope leakage of a large building air flow rates up to 25 m^3/s or more are to be supplied. The commercially available blower doors, as described in 6.3.1., may be insufficient for providing the required air flow rates. This may be achieved by combining several fans put in parallel.

Two exemplary systems are reported here, the BREFAN system, from BRE, Garston, UK, and one developped under contract to BRE by the Welsh school of Architecture, Cardiff, UK.

System used by the Welsh School of Architecture

The requirement that fans must fit into a standard fire exit in order to permit testing of the main loading door limits the diameter of the fans to approximately 24" (610 mm). Standard fans of this dimension (three phase supply) deliver approximately 4 m^3s^{-1}, although fans are available to special order that have double wound motors and can deliver a maximum flow rate of the order of 9 m^3s^{-1} (see attached equipment list). The limiting dimension on the fan forces to use a modular approach to the building of a pressurization rig, i.e. the rig consists of a number of smaller units rather than one large one. This has not posed any problems since larger buildings tend to have more fire exits than small ones.

The first rig consists of two fans, one mounted on top of the other and the whole set up fits into a standard fire exit opening. The top fan (Eurofoill CA 635) has a five speed stepped controller and delivers up to 4.1 m^3s^{-1}. The lower fan is a two speed Woods 610J, and can deliver the same maximum air flow rate. The duct lengths for each fan are 3 m.

The second rig consists of a Myson 24" In-Flight fan. This is a variable pitched in motion (VPIM) fan that delivers flow rates up to approximately 8.5 m^3s^{-1}. The duct length is 3 m.

The third and final rig consists of a Myson 24" single speed fan delivering approximately 8 m^3s^{-1}. The duct length is 3 m.

For each fan system, the measurement of volume flow rate is achieved using Wilson Flow Grids. These require a flow straightener to be fitted between the fan and the flow grid. Ours were based on the ACMA type flow straightener but with twice the recommended cell size. This cell size was demonstrated to be sufficiently small to produce laminar flow and yet have less flow resistance than a standard flow straightener. Two external pressure taps are normally employed, one upwind and one downwind of the building, and their outputs manifolded together. This has been found to stabilize the measurement of the internal-external static pressure difference.

	Fan type	Diameter mm	Max flow rate m^3/s	Manufacturer
Rig 1	Eurofoil CA635	635	4.1	Ziehll-Abegg, Germany
	Woods 610J	610	4.1	Woods of Colchester Essex, CO4 5AR
Rig 2	Myson 24" VPIM In-Flight Fan	607	8-5	Myson Fans Ltd Peartree Road Stanway Colchester CO3 5LD
Rig 3	Myson 24"	607	8	Myson Fans Ltd as above
	Wilson Flow Grid			Air Flow Developments Ltd Lancaster Road, High Wycombe, Surrey

BREFAN

The 'BREFAN' system consists of three identical fan pressurization units (see Figure 6.5), each drawing less than 3 kW of electrical power from conventional 13 amp sockets.

Each fan is 762 mm (30 inches) in diameter, is of the direct drive, single stage, axial flow type, and is capable of providing a flow rate of 5.5 m^3/s against a building envelope pressure difference of 50 Pa.

Air flow through each fan is measured using a conical inlet designed to British Standard *[BS 848, 1980]*.

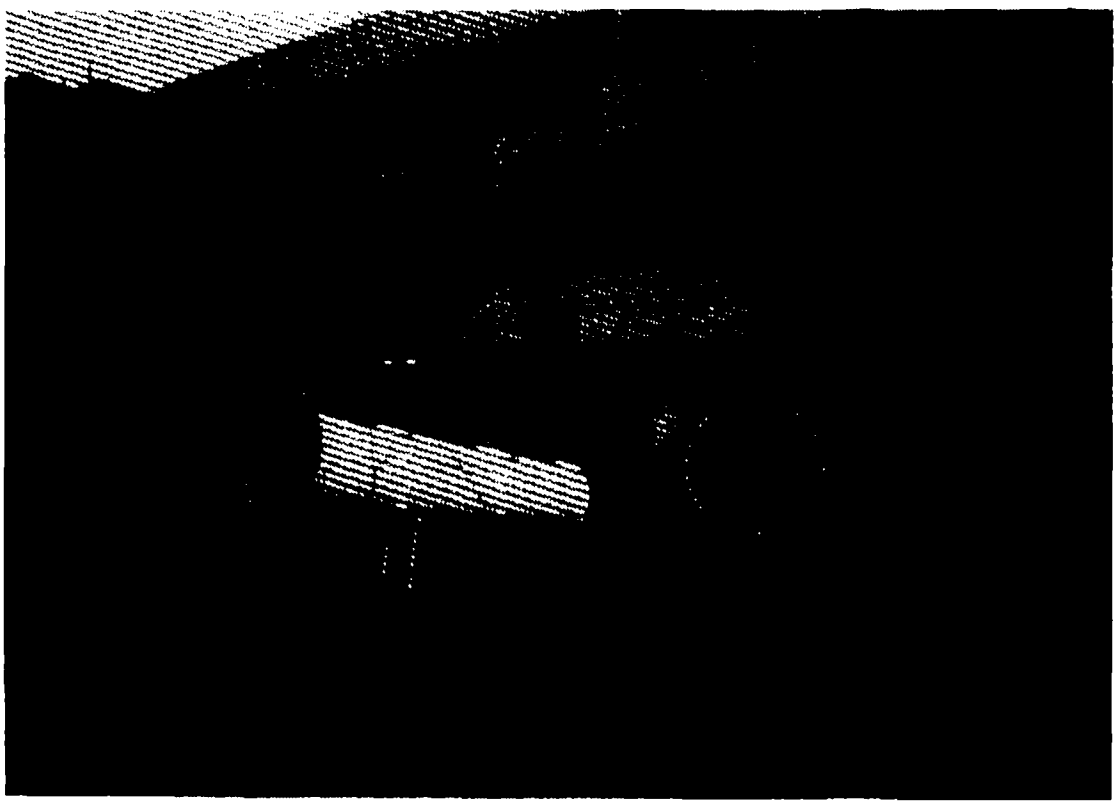


Figure 6.5.: Two BREFAN units installed in the BRE low energy office building.

On any particular building, the number of fan units used is set by that required to achieve the target envelope pressure difference. Single-phase to three-phase (variable-frequency inverter-type) speed controls are used to operate the fans from generally available single-phase power supplies and also to stabilize their speeds which would otherwise fluctuate during multiple-fan operation.

6.5. Available Equipment: Infrared Imaging or Thermographic Systems

These systems can be used together with depressurization during the cold season to locate the leaks in the building fabric.

Listed are systems with high thermal resolution, and most of them have digital image processing capabilities (exception is # 4).

The list is comprehensive but not assumed to be complete.

Only the headquarter addresses of the suppliers are given. In most cases there are local subcompanies (per continent or even country) or agencies (perhaps even more than one in each country).

Nr System	Supplier Typical
1 AGEMA Infrared Systems AB Box 3 S - 182 11 Danderyd, Sweden	Thermovision 0
2 Barr & Stroud Limited Caxton Street , Anniesland Glasgow G13 1HZ, England	Model IR 18
3 Florin & Scherler Arsenalstr. 40 CH-6010 Luzern, Switzerland	Thermoflir
4 Hughes Aircraft Company 6155 El Camino Real Carlsbad, Cal 92009, USA	Probeye
5 Inframetrics 12 Oak Park Drive Bedford, MA 01730, USA	Spectrotherm
6 JEOL Ltd. 1-2 Musashino 3-chome Akishima, Tokyo 196, Japan	Model JTG-3110/3210

***Table 6.3:** Available thermographic equipment.*

7. Airtightness Measurement Techniques Standards

The airtightness of buildings and building components can be evaluated using fan pressurization methods.

Several countries have developed standards relating to site measurements of building airtightness. A review of building airtightness and ventilation standard was published by the AIVC *[Colthorpe, 1990]*. Table 7.1 presents several of these standards, giving for each its country of origin, governing body, designation and title. Summaries of the standards referred to in Table 7.1. are presented below and table 7.2 compares the salient features.

Country	Body	Contact address	Designation	Title
Canada	CGSB	Canadian General Standard Board Ottawa K1A 1G6	CAN/CGSB 149.10-M86 [1986]	Determination of the Equivalent Leakage Area of Buildings by the Fan Depressurization Method
Nether-lands	NNI	Kalfjeslaan 2 Postbus 5059 NL-2600 Delft	NEN 2686 [1988]	Air Leakage of Buildings - Measurement Method
Nordic	NORD-TEST	Prästbordsgräden 2 SF-00340 Helsingfors 34	NT BUILD 220	Buildings: Local Air Tightness. [1983]
Norway	NSF	Haakon VII gate N-Oslo 1	NS-INSTA 130 [1981]	Air Tightness of Buildings Test Method
Sweden	BST	Drottning Kristinas Väg 73 S 11428 Stockholm	SS 02 15 51 [1987]	Buildings- Determination of Airtighness
USA	ASTM	1916 Race Street Philadelphia PA 19103, USA [1984]	ASTM E 779 [1987] ASTM E 783	Standard Test Method for Determining Air Leakage Rate by Fan Pressurization. Standard Test Method for Field Measurements of Determination of Air Leakage Through Installed Exterior Windows and Doors.
			ASTM E 1186 [1987]	Standard Practices for Air Leakage Site Detection in Building Envelopes
Interna-tional	ISO	1, Rue de Varembé Case Postale 56 CH-1211 Genève 20	ISO 6781 [1983]	Thermal Insulation - Qualitative Detection of Thermal Irregularities in Building Envelopes - Infrared Method.
			ISO 9972 [1991]	Thermal Insulation - Determination of Building Airtightness - Fan Pressurization Method.

Table 7.1.: Airtightness detection and measurement standards.

7.1. Canadian Standard CAN/CGSB - 149.10 - M86

This standard relates to a method for the determination of the airtightness of building envelopes. The method is applicable to small detached buildings (especially houses), but with appropriate modifications, it can be used for other buildings or parts of buildings.

A fan or fans are used to exhaust air from the building at rates required to maintain the specified pressure differences across the building envelope. With the complete envelope subjected to simultaneous and similarly directed air pressure, air flows and pressure differences are measured. Air flow is corrected to reference temperature and pressure and the relationship between the flow and the pressure difference is used to evaluate the equivalent leakage area of the building envelope .

The standard describes the apparatus required to perform the tests and the laboratory calibration of this apparatus. Preparation of the building and the setting up of the test equipment is given attention. A detailed description of the test procedure is given, and the process of evaluating the equivalent leakage area from the test data is presented in full. A standard format for the test report is given.

7.2. Netherlands Standards Nederlandse Norm NEN 2686

This standard is presently available only in the original language. The standard describes a technique for the pressurization or depressurization of building components or the building envelope. Although the standard applies to all types of buildings, special emphasis is placed on the measurement of dwellings.

To ensure accuracy a minimum of at least 6 pressure differences and corresponding flow rates must be measured. Pressure differences must be in the range of 15-100 Pa. The results can be shown graphically. The final result is a flow rate through the envelope at 10 Pa. For convenience an equivalent leakage area can be calculated using the equation presented in the standard. The results must be presented in accordance with the given standard reporting format.

7.3. Nordic Recommendation NORDTEST NT BUILD 220

This NORDTEST document describes a method for evaluating the air leakage characteristics of individual building components or joints between components under field conditions.

The object to be measured can be in any building or structure which can be exposed to a pressure difference. However, the surface of the object must be directly accessible and easy to border on the side where the measurement apparatus is to be placed. Thus a covering structure, such as a lowered ceiling which encloses an open air space against the object may prevent the measurement.

The test object will form part of the boundary of an enclosed room or building. A collection chamber is placed over the measured object. The chamber is equipped with a fan and a volume flow meter for evaluating the air flow rate through the test piece. A pressure measurement device is utilized to measure the pressure differential across the test component. A second fan is used to pressurize the room or building containing the test piece. This is used to balance the pressure between the room and the collection chamber, thus eliminating pressure can be provided by an auxiliary fan or the building's ventilation system. Once the required pressures have been balanced then the component flow rate and pressure difference measurements can be made.

This document describes the equipment required to perform the leakage test, the preparation of the building component or joint, the test procedure and the presentation and accuracy of the results.

7.4. Norwegian Standard NS-INSTA 130 and Swedish Standard SS 02 15 51

These nearly identical standards describe a method which applies to the determination of the rate of air leakage through the external envelope of a building resulting from a specified pressure difference. The method is designed to measure the total air leakage through the building elements or envelope surrounding a specific volume (a building or part of a building). A fan is used to supply air to or exhaust air from the building at rates required to maintain the specified pressure differences across the building envelope.

These standards are similar to the Canadian standard described in Section 7.1. except that they require that both pressurization and depressurization tests be performed on the building. Also the results of the test are presented not in terms of the equivalent leakage area but as the average air changes per hour at a pressure difference of 50 Pa across the building envelope.

The standard describes the apparatus required to perform the test, the preparation of the test building, the test procedure and the presentation of the results. The accuracy of the test is discussed and a standard reporting format for the test is presented.

7.5. UK Recommended Procedure From the BRE

This publication [Stephen, 1988] is written in the form of a code of practice and covers the significance of the method and its use, the requirements of the equipment used, the preparation and carrying out of the test and the data analysis.

Both pressurization and depressurization are required. the test should not be undertaken if the average wind speed is greater than Beaufort 3 (ie. about 5 m/s). Values of the air flow rates through the fan should be recorded close to pressure differentials of 55, 50, 45, 40, 30, 20, 10 and 5 Pa. The minimum

pressure differential should be below 10 Pa with the upper value not exceeding 55 Pa.

Corrections to air flow rates must be made to take account of the air density prevailing at the time of the test against that during calibration of the apparatus, and also if there is a temperature difference between indoor and outdoor in excess of 2.5 K.

7.6. USA Standards Related to Airtightness of Buildings

7.6.1. Determining Air Leakage Rate by Fan Pressurization

The test method *[ASTM E 779-87]* describes a standardized technique for measuring air leakage rates through a building envelope under controlled pressurization or depressurization. The test method consists of mechanical pressurization or depressurization of a building and measurements of the resulting air flow rates at given indoor-outdoor static pressure differences. From the relationship between the air flow rates and pressure differences the air leakage characteristics of a building envelope can be evaluated.

The standard, which is currently being updated, describes the significance and use of the test method, the apparatus required to perform the test, and the measurement and analytical procedures. Hazards involved in making pressurization measurements are noted, and a standard reporting format for the tests is presented.

7.6.2. Field Measurements of Air Leakage Through Installed Exterior Windows and Doors

This standard method *[ASTM E 783-84]* deals with the determination of the resistance of installed exterior windows and doors to air leakage resulting from static pressure differences. The method is applicable to window and door assemblies only. However, with adaption, the method can be used to determine the leakage through openings between the window or door assemblies and adjacent construction. A test consists of sealing a chamber to cover the interior or exterior face of a test specimen, supplying air to or exhausting air from the chamber at a rate required to maintain a specified static pressure across the specimen, and measuring the resultant air flow through the specimen.

This test method is similar to the Nordic Component Leakage method described. In this case however a second fan is not used to balance the pressure between the collection chamber and the room containing the component. Therefore the extraneous leakage through the collecting chamber must be evaluated before conducting the leakage test on the specimen.

The calibration procedure, which consists of sealing the specimen with a sheet of polythene film and performing a pressure test, is described in detail in the document. The document also contains sections dealing with the significance and use of the test methods, the apparatus required to perform the test, the preparation of the test specimen and the measurement procedure.

Calculations and the expression of the final results are examined in detail. Safety precautions and measurement accuracy are addressed and a Standard reporting format for the tests is presented.

7.6.3. Air Leakage Site Detection in Building Envelopes.

This standard *[ASTM E 1186-87]* describes different techniques for locating the sources of air leakage in building envelopes. Five methods of detection are presented together with their advantages and limitations. These methods are:

- combined building depressurization and thermography,
- building pressurization (or depressurization) and smoke tracers,
- building pressurization (or depressurization) and air flow measuring devices,
- sonic detection and location of leaks
- detecting a tracer gas after adding this tracer upstream of the leakage site.

7.7. International Standard ISO 9972

This International Standards Organization standard addresses the use of the mechanical pressurization or depressurization of a building or building component. It describes techniques for measuring the resulting air flow rates at given indoor-outdoor static pressure differences. From the relationship between air flow rates and pressure differences, the air leakage characteristics of a building envelope can be evaluated.

This document is applicable to small temperature differentials and low wind pressure conditions. For tests conducted in the field, it must be recognized that field conditions may be less than ideal.

Nevertheless, strong winds and large indoor-outdoor temperature differentials should be avoided. The proper use of this standard requires a knowledge of the principals of air flow and pressure measurements.

This proposed standard is intended for the measurement of the air tightness of building envelopes of single zone buildings. For the purpose of this standard, many multi-zone buildings can be treated as single-zone buildings by opening interior doors or by inducing equal pressures in adjacent zones.

Results of the field measurements are not intended to characterize the air leakage of an isolated component but the air leakage of the component and its junction with the building envelope under given conditions of installation.

The standard has sections dealing with the apparatus required for the test, the preparation of the building, the measurement procedure, data and error analysis, and accuracy. A standard reporting format for the test is included.

7.8. Comparison of Airtightness Measurement Standards

Several of the standards discussed above deal with the evaluation of the airtightness of the entire building envelope. Table 7.2 presents a comparison of some of the salient features of these standards.

The parameters compared are:

Recommended fan flow capacity: The fan used must have the capacity to produce the flow rates and pressure differentials required by the standards. Several standards give guidance as to the flow rates required to perform the test.

Pressure tap location: All standards require a pressure tap within the building and in order to evaluate the pressure difference across the envelope, pressure tap(s) must also be made outside the building shell. Standards vary in the number and location of pressure tap(s) specified.

Differential pressure range: The specified pressure differential across the building envelope varies both in direction and range. All standards however encompass the range 0-50 Pa in either over pressure or under pressure.

Limiting conditions: Natural fluctuating pressure differences across the envelope, caused by wind and temperature effects, affect the accuracy of fan pressurization tests. Several standards place limits on natural pressure differences, wind speed or temperature difference. If these limits are exceeded then the results of the measurement may be invalid. In this column, v is the wind speed and Δp_o is the natural pressure differential across envelope without fan or when the pressurization fan is off and its opening closed.

Expression of results: Each standard requires the final results of the test to be expressed in a slightly different form. This is important when comparing the results of tests performed in compliance with individual standards. In this column, ELA is used for equivalent leakage area, ACH for air change rate and C, n for the flow coefficients in equation (5.1).

Accuracy: Stated accuracy requirements for each standard focus on measurements of air flow rate and pressure difference across the building envelope.

In addition to the specific points described above, standards also vary in building preparation requirements. This factor should also be taken into account if comparing the results of tests performed to comply with a specific standard.

Standard	Required Fan Flow Capacity	Pressure Tap Location	Differential Pressure Range	Limiting Conditions	Expression of Results	Required Accuracy
ASTM E 779-87	Not stated	One location Not stated	12.5 - 75 Pa over- or under-pressure	$v < 2$ m/s $5 < \theta < 35$ °C	Plot $q(\Delta p)$ ELA	Airflow 5 % Δp 2.5 Pa
BRE code	Sufficient to produce Δp of 55 Pa	One tap 10 m from building ending in a T-piece	5 to 55 Pa over- and under-pressure	$v < 5$ m/s	Plot $q(\Delta p)$ C, n ACH @ 50 Pa	Airflow 5 %
CAN/CGSB 149.10-M86	Maximum 1.5 - 2.5 m^3/s	≥ 4 taps around building and averaging container	0 - 50 Pa Under-pressure	$v < 5.6$ m/s	ELA	Airflow 5 % Δp 2 Pa
ISO 9972	Sufficient to produce Δp of 60 Pa	Ideally near neutral plane	10 to 60 Pa over - or under-pressure	$\Delta p_o < 3$ Pa	C, n ELA	Airflow 5 % Δp 5 %
NEN 2686	Maximum 1.2. m^3/s	One tap at building facade	15 to 100 Pa over - or under-pressure	$\Delta p_o < 5$ Pa $v < 6$ m/s	C, n Flow rate @ 1 and 10 Pa	Airflow 5 % Δp 5 %
NS-INSTA 130 SS 02 15 51	Sufficient to produce Δp of 55 Pa	One tap 10 m from building ending in a T-piece	0 to 55 Pa over - and under-pressure	$v < 6$ m/s 10 m from building	ACH @ 50 Pa	Airflow 6 % Δp 3 Pa Overall 10 %

Table 7.2: *Airtightness measurement standards. Comparison of salient features [Colthorpe, 1990].*

8. References

After the sign # are AIRBASE numbers. If the number is between square brackets [], it relates to a book containing the quoted reference. AIRBASE numbers between brackets () relate to similar texts with a reference other than the quoted one.

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Part III
Air Flow Measurement Methods

Symbols and Units

A_{ji}	cofactors of the element Q_{ij} in $\underline{\underline{Q}}$	[kg/s]
$\underline{\underline{C}}$	matrix of the net mass concentrations C_{ik} - C_{0k} of gas k in zone i	[kg/kg]
$\underline{\underline{c}}$	matrix of the net volume concentrations c_{ik} - c_{0k} of gas k in zone i	[m^3/m^3]
C_{ik}	mass concentration of tracer k in zone i	[kg/kg]
c_{ik}	volume concentration of tracer k in zone i	[m^3/m^3]
$\underline{\underline{G}}$	air change matrix. $\underline{\underline{G}} = -\underline{\underline{M}}^{-1}\,\underline{\underline{Q}}$	[s^{-1}]
$\underline{\underline{M}}$	matrix of masses of air contained in each zone	[kg]
m_i	mass of air in zone i	[kg]
m_{ik}	mass of tracer k in zone i	[kg]
M_k	molecular mass of tracer k	[kg/Mole]
n	air change rate	[s^{-1}]
P_{ji}	probability that a particle released in *zone i* passes into zone j	[-]
p	pressure	[Pa]
$\underline{\underline{Q}}$	mass flow matrix containing, in the off-diagonal elements, the mass flow rates $-Q_{ij}$ going from zone j to zone i, with $j \neq i$. The diagonal elements with $j=i$ are the sum of the flow rates leaving zone i.	[kg/s]
$\underline{\underline{q}}$	volume flow matrix	[m^3/s]
Q_{ij}	mass air flow rate from zone j to zone i	[kg/s]
q_{ij}	volume air flow rate from zone j to zone i	[m^3/s]
R	the molar gas constant: $R = 8.31396$	[J/(mole.K)]
$\underline{\underline{S}}$	matrix of the mass flow rates S_{ik} of tracer k in zone i.	[kg/s]
$\underline{\underline{s}}$	matrix of the volume flow rates s_{ik} of tracer k in zone i.	[m^3/s]
S_{ik}	mass injection rate of tracer k in zone i	[kg/s]
s_{ik}	volume injection rate of tracer k in zone i	[m^3/s]
T_o	absolute temperature of outdoor air	[K]
T_i	absolute temperature in zone i	[K]
T_k	absolute temperature of tracer k when injected	[K]
W_{ij}	elements of the inverse $\underline{\underline{Q}}^{-1}$	[s/kg]
W_{ij}	with $j \neq i$: transfer index from zone j to zone i	[s/kg]
t	time	[s]
U_i	$= 1/T_{ii}$: local purging flow rate	[kg/s]
$\underline{\underline{V}}$	diagonal matrix whose elements are the volumes of air V_i contained in each zone	
V_i	volume of zone i	[m^3]
V_{ik}	volume of tracer k in zone i	[m^3]
x	dummy variable	
$\langle x \rangle_t$	average of the variable x over time period t	

Δ	indicates a difference
Δc	$= c - c_o$ is the difference in tracer gas concentration between indoor and outdoor air . . . . . [-]
δ_{ij}	Kronecker delta: $\delta_{ij} = 1$ if $i=j$, $\delta_{ij} = 0$ if $i \neq j$
$\underline{\underline{\rho}}$	diagonal matrix of the air densities in the zones, ρ_i . . . . . [kg/m^3]
ρ_i	density of air in zone i: $\rho_i = m_i/V_i$ . . . . . [kg/m^3]
ρ_{ik}	density of tracer k in zone i: $\rho_i^k = m_i^k/V_i^k$ . . . . . [kg/m^3]
ρ_k	density of tracer k when injected . . . . . [kg/m^3] $\underline{\underline{S}}$
τ_n	nominal time constant. $\tau_n = 1/n$ . . . . . [s]
$\underline{\underline{\tau}}$	matrix defined as $\underline{\underline{\tau}} = \underline{\underline{Q}}^{-1} \underline{\underline{M}}$ . . . . . [s]
$\langle \tau_i \rangle$	room mean age of air . . . . . [s]

1. Introduction, Objective of Measurements

In this Part of the guide, the various methods involving tracer gases for the measurements of air flows in buildings are presented. These methods may be used to answer the following questions:

- what is the room ventilation rate? (Note: the methods presented in Part IV are best suited to answer the question: How *well* is a room ventilated?)
- What is the energy required to heat or cool the fresh air entering the room?
- What is the energy lost in exhaust air?
- What is the risk that a contaminant leaves the space where it is generated to reach another space where it may be dangerous?
- What are the actual air flow rates in a building, for given meteorological and HVAC operating conditions?

To answer the first three questions, the flow rates between the space and outdoors should be known and these can be assessed with one measurement using single tracer methods. Today, in 1990, there is not enough statistical information on air change rates in buildings. Several publications recommend minimum and maximum air change rates *[Trepte, Haberda, 1989]* but it is seldom that these recommended air change rates are verified in the field.

The situation is the same for the fourth question: the contaminant can be simulated with a single tracer, its spreading can be easily measured but very few control measurements are performed. If there are several contaminants generated at various places, these contaminants could be simulated with several non-toxic tracers.

So, in order to know more about the reality of ventilation in buildings and to improve indoor air quality, more measurements are needed.

Multizone, multitracer measurements are best to answer the last question. However, this technique is expensive and involves substantial analytical effort. For these reasons, this approach is at present mainly used for research purposes.

2. Basic Equations

In this chapter, the basic equations representing tracer gas concentrations and air flows in multizone buildings are presented. The definitions and the hypotheses covering the interpretation of cases where the air temperature is neither homogeneous nor constant are included. These equations are used to interpret both single- and multi-tracer gas measurements.

2.1. Introduction

The equations for interpreting tracer gas measurements are based on the conservation of *mass* of tracer and of *mass* of air, although it is often *volumes* which are measured and *volume flow rates* which are determined. Moreover, there are numerous definitions of tracer gas concentration, e.g. parts per volume or parts per mass, mass of tracer per volume of air or even molarity or partial pressures (these latter two definitions are not used in this topic). It is important, therefore, to define all the parameters explicitly at the outset.

The objective of this chapter is to present the hypotheses together with the resulting equations. This theory also applies to the case of non uniform air density (or air temperature).

2.2. Basic Assumptions

Let us assume that there are N zones in the measured building, denoted by the suffixes i and j, into which, in principle, N different tracers, denoted by the index k, are injected. In principle, each zone receives only one tracer, but the equations presented allow the use of several gases in the same zone. No tracer is injected in the outside air (zone 0), which is assumed to be of infinite volume. However, the tracer concentration in that zone may differ from zero.

The variables (as appropriate) are assumed to be time dependent.

The multizone tracer gas theory is based on the conservation of the mass of tracer gas and of air and on the following three assumptions:

1) ***In each zone, tracer concentrations are always homogeneous.***

2) ***The atmospheric pressure is constant.***

3) ***The injection of tracer gas does not change the density of air.***

The first assumption is the weakest. In practice, homogeneous concentration may only be achieved by the use of mixing fans, but these fans may affect infiltration conditions. This influence may be avoided however by following the precautions presented in Section 5.2.4.

The other two hypotheses are easily satisfied, since the short time relative variations of atmospheric pressure are of the order of 0.01 % (daily variations of the order of a percent) and tracer gases are generally injected at relatively low concentrations (10^{-4} in volume or less).

2.3. Conservation of the Masses of Air and Tracer Gas, k, in the Zone i

In each zone, the rate of change of the air mass m_i equals the sum of the incoming flows minus the sum of the outgoing flows:

$$\frac{dm_i}{dt} = \sum_{j=0}^{N} Q_{ij}\,(1-\delta_{ij}) - \sum_{j=0}^{N} Q_{ji}\,(1-\delta_{ij}) \qquad (2.1)$$

Change in mass | Incoming flow rates | Outgoing flow rates

The conservation equation of the mass of tracer, k, in the zone, i, states that the change of tracer mass within the zone is the sum of the mass of injected tracer and the mass of tracer contained in the air entering the zone, minus the mass of tracer contained in the outgoing air:

$$\frac{dm_{ik}}{dt} = S_{ik} + \sum_{j=0}^{N} C_{kj}\,Q_{ij}\,(1-\delta_{ij}) - C_{ik} \sum_{j=0}^{N} Q_{ji}\,(1-\delta_{ij}) \qquad (2.2)$$

Variation = Injection + Inflow - Outflow

An extension of assumption (1) is implicit in this equation, that is:

4) ***The air flows entering a zone do not modify the homogeneity of the concentration of tracer gases in that zone, i.e., an immediate and perfect mixing is assumed.***

2.4. Complete Systems of Equations

If there are N tracers or N different sets of measurements using a single tracer injected at various rates in the various zones, equations (2.1) and (2.2) above give a full set of $N(N+1)$ equations. Therefore, this allows the $N(N+1)$ flows between all the zones including the outdoor air as the zone zero to be determined. There are two methods to transform this set of equations before solving. Since they each have various advantages and disadvantages, they are both described below.

2.4.1. Global System of Equations

The most common technique to be found in the literature *[e.g. Sinden, 1978], [Sherman, Grimsrud, Condon, Smith, 1980], [Perrera, 1982], [Sandberg, 1984, Sherman, 1988]* is the following:

Let us express by Q_{ii} the sum of all the flows going out of the zone i:

$$Q_{ii} = \sum_{j=0}^{N} Q_{ji} (1-\delta_{ij}) \tag{2.3}$$

Using the above notation and taking apart the flows coming from outside, equation (2.2) becomes:

$$\frac{dm_{ik}}{dt} = S_{ik} + \sum_{j=1}^{N} C_{jk} Q_{ij} (1-\delta_{ij}) + C_{0k} Q_{i0} - C_{ik} Q_{ii} \tag{2.4}$$

Since any change in the outdoor level of tracer gas concentrations, C_{0k}, will be negligible, these levels are the base levels of tracer gas concentrations anywhere else. In this case the tracer mass balances expressed in equations (2.4) can be written in a matrix form:

$$\frac{d}{dt}[\underline{\underline{M}}\,\underline{\underline{C}}] + \underline{\underline{Q}}\,\underline{\underline{C}} = \underline{\underline{S}} \tag{2.5}$$

where each row of the N x N matrices $\underline{\underline{M}}\,\underline{\underline{C}}$, $\underline{\underline{Q}}\,\underline{\underline{C}}$ and $\underline{\underline{S}}$ corresponds to a zone and each column to a given tracer gas. More specifically:

$\underline{\underline{M}}$ is a diagonal matrix whose elements are the masses of air contained in each zone:

$$m_i = \rho_i V_i \text{ or } \underline{\underline{M}} = \underline{\underline{\rho}}\,\underline{\underline{V}}$$

with $\underline{\underline{\rho}}$ is the diagonal matrix of the air densities in the zones, ρ_i, and $\underline{\underline{V}}$ the diagonal matrix of the volumes of the zones, V_i.

$\underline{\underline{C}}$ contains the differences in mass concentrations $C_{ik} - C_{0k}$ of gas k in zone i

$\underline{\underline{S}}$ is the matrix containing the mass flow rates S_{ik} of the tracer, k, in zone i. In usual measurements, this matrix is diagonal.

$\underline{\underline{Q}}$ is the so-called **flow matrix** containing, the off-diagonal elements ($j \neq i$) being $-Q_{ij}$, where Q_{ij} represents the mass flow rates from zone j to zone i. The diagonal elements with $j=i$ contain the sum of the flows leaving the zone i, as defined in (2.3).

In equation (2.5), i and j run from 1 to N and this system results in N^2 equations for the interzonal flows. The mass flows to and from outside are given by equations (2.1).

2.4.2. Zone by Zone Systems of Equations

Another presentation of the same model is found in *[Roulet, Compagnon, 1989]*. It is obtained as follows:

Combining equations (2.1) and (2.2), then taking into account that $m_{ik} = m_i C_{ik}$, and using:

$$\frac{dm_{ik}}{dt} = m_i \frac{dC_{ik}}{dt} + C_{ik} \frac{dm_i}{dt} \tag{2.6}$$

we finally get:

$$m_i \frac{dC_{ik}}{dt} = S_{ik} + \sum_{j=0}^{N} (C_{jk} - C_{ik}) Q_{ij} (1-\delta_{ij}) \tag{2.7}$$

For each zone i, the N equations (2.7) give the N flows, Q_{ij} ($j = 0...i-1, i+1,...N$). The flows, Q_{ji}, are obtained from the same equations applied to zone j and the remaining flows, Q_{0i}, are given by equations (2.1).

2.5. Further Interpretation of the Flow Matrix

The final result of the measurements is the flow matrix $\underline{Q}$ defined above. Further information can be deduced from this flow matrix, as shown in the following discussion.

2.5.1. Properties of the Flow Matrix

From the structure of the flow matrix, $\underline{Q}$, and the air mass conservation equations, it can be seen that $\underline{Q}$ is diagonally dominant, that is, in absolute values, the diagonal elements are greater than or equal to the sum of all the other elements in the respective rows or columns. The non-diagonal elements are nevertheless all negative.

The following relations can be obtained:

The **total infiltration air flow rate** to each zone, i, is easily obtained by summing the **columns** of the flow matrix:

$$Q_{i0} = \sum_{j=1}^{N} Q_{ij} \tag{2.8}$$

And the **total exfiltration air flow rate** from each zone, i, is the sum of the **lines** of the flow matrix:

$$Q_{0i} = \sum_{i=1}^{N} Q_{ij} \tag{2.9}$$

If there is no totally isolated chamber in the measured system, and if there is some air exchange with outside (as it is the case with any usual building), the flow matrix determinant, $|\underline{Q}|$, is positive and $\underline{Q}$ has an inverse, $\underline{Q}^{-1}$ *[Sandberg, 1984]*.

The elements of the inverse $\underline{Q}^{-1}$ are given by:

$$W_{ij} = \frac{A_{ji}}{|\underline{Q}|} \tag{2.10}$$

where A_{ji} are the cofactors of the element Q_{ij} in $\underline{Q}$. The cofactors, A_{ii}, of the diagonal elements are positive and those of the off-diagonal elements, A_{ji}, are zero or positive.

It follows that the largest elements in the rows or columns of $\underline{Q}^{-1}$ are the diagonal elements.

2.5.2. Physical Interpretation of the Inverse Flow Matrix.

The basic equations applied to the case where a constant flow rate, S_{ik}, of a contaminant, k, is applied in each zone, i, leads to an equilibrium concentration (for constant air flow rates) which is:

$$\underline{C}(\infty) = \underline{Q}^{-1} \underline{S} \tag{2.11}$$

It follows that the equilibrium concentration in room, j, resulting from a contaminant, k, released only in room, i is:

$$C_{jk}(\infty) = W_{ji} S_{ik} \tag{2.12}$$

and the non-diagonal elements of $\underline{Q}^{-1}$ are hence the **transfer indexes** defined in *[Sandberg, Sjöberg, 1983]*. Since he also defined the **local purging flow rate**, U_i, in chamber, i, as the rate at which the

contaminant is eliminated:

$$U_i = S_{ik}/C_{ik} = 1/W_{ii} \tag{2.13}$$

we see that the diagonal elements of $\underline{\underline{Q}}^{-1}$ are the reciprocal of the local purging flow rate.

Moreover, the probability that a particle released in zone i passes into the zone j can be defined as:

$$P_{ji} = W_{ji}\, U_j \tag{2.14}$$

and the $\underline{\underline{Q}}^{-1}$ matrix can be re-written as:

$$\underline{\underline{Q}}^{-1} = \begin{bmatrix} \frac{1}{U_1} & \frac{P_{12}}{U_1} & \cdots & \frac{P_{1N}}{U_1} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \frac{P_{N1}}{U_N} & \frac{P_{N2}}{U_N} & \cdots & \frac{1}{U_N} \end{bmatrix} \tag{2.15}$$

Using a simple inversion of the flow matrix, much information on the possible spreading of contaminants (e.g., transmission probabilities and purging flow rates) can be obtained.

2.5.3. τ Matrix and Mean Age of Air

The τ matrix is defined as:

$$\underline{\underline{\tau}} = \underline{\underline{Q}}^{-1}\, \underline{\underline{M}} \tag{2.16}$$

or, under the assumptions of constant, uniform temperature:

$$\underline{\underline{\tau}} = \underline{\underline{q}}^{-1}\, \underline{\underline{V}} \tag{2.17}$$

It is shown *[Sandberg, 1984]* that the row sums of the τ matrix are the mean age of air† in the corresponding rooms:

$$\langle \tau_i \rangle = -\sum_{j=1}^{N} \tau_{ij} \tag{2.18}$$

This relation enables the measurement of the room mean age of air to be made, even in rooms where there are several outlets or several ways for the air to leave the room.

2.6. Equations for Volume Flow Rates

Sections 2.3 to 2.5 contains equations based on mass flow rates and mass concentrations. However, for practical reasons, volume flow rates and volume concentrations are of common use. Therefore, the basic equations are adapted below.

The mass concentration is, by definition:

$$C_{ik} = \frac{m_{ik}}{m_i + m_{ik}} = \frac{\rho_{ik}\, V_{ik}}{\rho_i\, V_i + \rho_{ik}\, V_{ik}} \tag{2.19}$$

Hence, the mass of the tracer k in the zone i is:

$$m_{ik} = \rho_{ik}\, V_{ik} = \frac{\rho_i\, V_i\, C_{ik}}{1 - C_{ik}} \approx \rho_i\, V_i\, C_{ik} \tag{2.20}$$

since $C_{ik} << 1$.

Taking account for the density correction, equation (2.2) can be rewritten in terms of volume flows, with the same assumptions (1 - 4) as before:

† See Section 2.1 of Part IV for more information on the age of air.

$$\frac{d}{dt}(\rho_i V_i C_{ik}) = \rho_k s_{ik} + \sum_{j=0}^{N} \rho_j C_{jk} q_{ij} (1-\delta_{ij}) - \rho_i C_{ik} \sum_{j=0}^{N} q_{ji} (1-\delta_{ij}) \quad (2.21)$$

If we replace in equation (2.21) the mass concentration by the volume concentrations, we obtain:

$$\frac{d}{dt}(\rho_{ik} V_i c_{ik}) = \rho_k s_{ik} + \sum_{j=0}^{N} \rho_{jk} c_{jk} q_{ij} (1-\delta_{ij}) - \rho_{ik} c_{ik} \sum_{j=0}^{N} q_{ji} (1-\delta_{ij}) \quad (2.22)$$

The tracer density is defined by $\rho_{ik} = m_{ik}/V_{ik}$ where the volume, V_{ik}, is defined at atmospheric pressure, p. Using the perfect gas law for tracer k:

$$p V_{ik} = m_{ik} R T_i / M_k \quad (2.23)$$

where R is the molar gas constant, $R = 8313.96$ [J/(K, kMole)], M_k the molar mass of the tracer, k, and T_i is the absolute temperature of zone i. The density of tracer k in zone i can be computed:

$$\rho_{ik} = \frac{p M_k}{R T_i} \quad (2.24)$$

and substituted in equation (2.22). Dividing this equation by $p M_k$, we get:

$$\frac{d}{dt}\left[\frac{V_i c_{ik}}{T_i}\right] = \frac{s_{ik}}{T_k} + \sum_{j=0}^{N} \frac{c_{jk} q_{ij} (1-\delta_{ij})}{T_j} - \frac{c_{ik}}{T_i} \sum_{j=0}^{N} q_{ji} (1-\delta_{ij}) \quad (2.25)$$

The left hand side of this equation can be expanded as follows:

$$\frac{d}{dt}\left[\frac{V_i c_{ik}}{T_i}\right] = \frac{V_i}{T_i} \frac{dc_{ik}}{dt} - \frac{V_i c_{ik}}{T_i^2} \frac{dT_i}{dt} \quad (2.26)$$

since V_i is constant.

In equations (2.25) and (2.26), as everywhere else in this chapter, the temperature of the volume flow rate, q_{ij}, is the temperature T_j of zone j, from which the flow comes.

The method used for developing equations (2.25) and (2.26) can also be used for air mass conservation, except that, here, the tracer is the air itself, which means that:

- there is no air injection flow rate ($s_{ik} = 0$)
- concentrations are all unity ($c_{ik} = 1$, assumption 3).

This air mass conservation equation then becomes:

$$-\frac{V_i}{T_i^2} \frac{dT_i}{dt} = \sum_{j=0}^{N} \frac{q_{ij} (1-\delta_{ij})}{T_j} - \sum_{j=0}^{N} \frac{q_{ji} (1-\delta_{ij})}{T_i} \quad (2.27)$$

Equation (2.7) can also be written as a volumetric flow balance equation. Combining equations (2.25), (2.26) and (2.27), the time derivative of the temperature and the air flow rates, q_{ji}, disappear and hence:

$$\frac{V_i}{T_i} \frac{dc_{ik}}{dt} = \frac{s_{ik}}{T_k} + \sum_{j=0}^{N} \frac{(c_{jk} - c_{ik})}{T_j} q_{ij} (1-\delta_{ij}) \quad (2.28)$$

Equation (2.27) can be rewritten as:

$$q_{0i} = T_i \sum_{j=0}^{N} \frac{q_{ij} (1-\delta_{ij})}{T_j} - \sum_{j=1}^{N} q_{ji} (1-\delta_{ij}) + \frac{V_i}{T_i} \frac{dT_i}{dt} \quad (2.29)$$

Finally, equations (2.28) and (2.29) give a system of $N+1$ equations for $N+1$ unknowns, q_{ij}, for each zone, i.

2.7. Simplified Equations

To derive a simpler form often encountered in the literature *[e.g. Sinden, 1978; Sherman, Grimsrud, Condon, Smith, 1980; Perrera, 1982]* from the above equations, we need two more assumptions; these are:

*5) **The air temperature, and hence the air density, does not vary with time.***

*6) **The air temperature, and hence the air density, is uniform throughout the inside and the outside of the building.***

Assumption (5) is more important than it appears. It is needed in order to make the second term of the right hand side of equation (2.26) negligible compared to the first term, that is:

$$\frac{V_i}{T_i}\frac{dc_{ik}}{dt} >> \frac{V_i c_{ik}}{T_i^2}\frac{dT_i}{dt} \tag{2.30}$$

The first term contains the time derivative of the concentration, which can be very small or even zero if the constant concentration technique is used. In this case, even very small temperature variations might be too large to satisfy the fifth assumption.

This means that assumption (5) can be replaced by the following:

*(5) **The relative variations of the temperature in the zone i are negligible when compared to the relative variations of the concentration of any tracer in this zone.*** That is:

$$\frac{1}{T_i}\frac{dT_i}{dt} << \frac{1}{c_{ik}}\frac{dc_{ik}}{dt} \tag{2.31}$$

Assumption (6) may be adequately satisfied if the temperatures of the various zones do not differ significantly, if the volume of injected tracer is measured at the air temperature in the building and finally if the measured building is neither heated nor cooled. Relative temperature or density differences of up to 10 % might be reached in cases where indoor-outdoor temperature difference is large (e.g. 30 K).

If the realistic assumption, that all internal temperatures are constant and equal but different from a constant outdoor temperature, T_0, is adopted, then:

$$T_i = T \qquad \frac{dT_i}{dt} = 0 \qquad \text{and} \qquad \frac{dm_i}{dt} = 0 \quad \text{for any } i>0 \tag{2.32}$$

and equation (2.5) becomes:

$$\underline{\underline{\rho}}\,\underline{\underline{V}}\frac{d\underline{\underline{C}}}{dt} + \underline{\underline{Q}}\,\underline{\underline{C}} = \underline{\underline{S}} \tag{2.33}$$

By matrix multiplication of equation (2.33) at the left by $\underline{\underline{Q}}^{-1}$ and using the definition of the t matrix:

$$\underline{\underline{\tau}}\frac{d\underline{\underline{C}}}{dt} + \underline{\underline{C}} = \underline{\underline{Q}}^{-1}\,\underline{\underline{S}} \tag{2.34}$$

we get a system of equations which may be used for the interpretation of decay measurements in which $\underline{\underline{S}} = \underline{\underline{0}}$.

In volume flow terms, we get, from equation (2.28):

$$V_i\frac{dc_{ik}}{dt} = s_{ik} + \sum_{j=1}^{N}(c_{jk} - c_{ik})\,q_{ij}\,(1-\delta_{ij}) + \frac{T}{T_0}q_{i0}(c_{0k} - c_{ik}) \tag{2.35}$$

In this case, the air mass conservation equations give:

$$q_{0i} = q_{i0}\frac{T}{T_0}\sum_{j=1}^{N} q_{ij}\,(1-\delta_{ij}) - \sum_{j=1}^{N} q_{ji}\,(1-\delta_{ij}) \tag{2.36}$$

By applying both assumptions 5 and 6 to equation (2.33), the temperature effect is completely

neglected and we get the simplified equations which are, in the zone by zone form:

$$V_i \frac{dc_{ik}}{dt} = s_{ik} + \sum_{j=0}^{N} (c_{jk} - c_{ik})\, q_{ij}\,(1-\delta_{ij}) \tag{2.37}$$

By taking the outdoor concentrations, c_{0k}, as zero or as the base levels, equation (2.35) reduces to:

$$V_i \frac{dc_{ik}}{dt} = s_{ik} + \sum_{j=1}^{N} c_{jk}\, q_{ij}\,(1-\delta_{ij}) - c_{ik}\, q_{ii} \tag{2.38}$$

which is the usual, simplified way of expressing the tracer concentration. In a matrix form, it gives:

$$\underline{\underline{V}} \frac{d\underline{\underline{c}}}{dt} + \underline{\underline{q}}\,\underline{\underline{c}} = \underline{\underline{s}} \tag{2.39}$$

where:

$\underline{\underline{V}}$ is a diagonal matrix whose elements are the volumes of air contained in each zone

$\underline{\underline{c}}$ is the concentration matrix, containing the differences in volume concentrations, $c_{ik} - c_{0k}$, of gas k in zone i

$\underline{\underline{s}}$ is the matrix containing the volume flow rates, s_{ik}, of tracer k in zone i

$\underline{\underline{q}}$ is the unknown matrix containing, in the off-diagonal elements, the volume flow rates, $-q_{ij}$, going from zone j to zone i, with $j \neq i$. The diagonal elements with $j=i$ contain the sum of flows leaving zone i:

$$q_{ii} = \sum_{j=0}^{N} q_{ji}\,(1-\delta_{ij}) \tag{2.40}$$

And the conservation of air mass (2.1) becomes simply a conservation of total volume flow:

$$\sum_{j=0}^{N} q_{ij}\,(1-\delta_{ij}) = \sum_{j=0}^{N} q_{ji}\,(1-\delta_{ij}) = q_{ii} \tag{2.41}$$

2.8. Single Zone

For a single zone, $i=1$, $j=0$, only one tracer is needed and equations (2.28) and (2.29) simplify to:

$$\frac{V}{T}\frac{dc_1}{dt} = \frac{s}{T} - \frac{(c_1 - c_0)}{T_0}\, q_{10} \tag{2.42}$$

and

$$q_{01} = \frac{T_1}{T_0}\, q_{10} + \frac{V_1}{T_1}\frac{dT_1}{dt} \tag{2.43}$$

Moreover, assuming a constant and homogeneous temperature, or if all volume flow rates are taken at inside density *[Sherman, 1990]*, equations (2.40) and (2.41) become:

$$V_1 \frac{dc_1}{dt} = s_1 + (c_0 - c_1)\, q_{10} \quad \text{and} \quad q_{01} = q_{10} \tag{2.44}$$

respectively. Finally, the tracer gas concentration can be either zero or taken as reference concentration. Noting:

$$\Delta c = c - c_o \tag{2.45}$$

equation 2.42 becomes:

$$\frac{V}{T}\frac{dc_1}{dt} = \frac{s}{T} - \frac{\Delta c}{T_0}\, q_{10} \tag{2.46}$$

or, for homogeneous density:

$$V_1 \frac{dc_1}{dt} = s_1 + \Delta c\, q_{10} \tag{2.47}$$

3. Principles of Different Methods for Determining Outdoor Air Flow Rates into a Building and Interzonal Air Flow Rates

3.1. Introduction

In chapter 2 the equations for mass conservation of both tracer gases and air were given. The equations were formulated as a system of equations for N interconnected zones. Within each zone, mixing is assumed to be complete. Normally each room constitutes a zone and the zone volumes are assumed to be known. The system of mass conservation equations contains a flow matrix where the entries are the interzonal flows and the flows between the zones and outdoor. In a building consisting of N zones, there are $N^2 - N$ interzonal flow rates and $2N$ flow rates between the zones and the outside. This makes a total of $N(N + 1)$ flow rates. The same number of equations is required to determine these flow rates.

These equations are obtained by conservation of masses of air and of the tracer gas in each zone. We may obtain a sufficient number of equations either by repeating the measurement procedure N times (assuming constant air flow rates) or by simultaneously using N different tracer gases.

From the above follows that the unknown number of flow rates increases dramatically with the number of rooms. Already, in a small house consisting of only 5 rooms, there are a total of 30 flow rates. This is a very large number in this context and it is a laborious task to estimate all these flow rates. As a consequence there is a practical upper limit to the number of flows that can be determined by measurements.

The interzonal flow rates are often buoyancy driven which makes them vulnerable to changing temperatures. In addition flow reversal frequently occurs within short time intervals. For example, radiators with an on-off control may reverse flow rates between rooms. Therefore the interzonal flow may frequently change in both direction and magnitude as a function of time and could be more difficult to determine than air flow rates to and from outdoors.

Since the effect of errors due to non complete mixing and other sources is more easily discussed in single zone situations, we begin with this situation in the following sections.

3.2. Zonal Representation of a Building.

The first step is to represent a given building as a collection of zones. This is something that requires considerable experience and skill and it is therefore very difficult to give general guidance. However there are some rules of thumb; these include:

- Rooms with very large flow rates between each other should be treated as a single well-mixed zone, treating them as separate zones will lead to an ill-conditioned problem.
- Corridors, staircases or passages that connect several rooms must often be divided into several zones.

3.3. Complete mixing

The basic idealization made in this context is the assumption of complete mixing within each zone. First of all, all the injected gas must be completely mixed with room air. For example, if a fraction of the gas is immediately lost after injection, then complete mixing is not achieved.

Furthermore, one must have uniform conditions throughout the whole space and the tracer gas concentration must therefore be the same throughout any zone. This requires that both tracer gas and air are mixed uniformly within the zone. There are two aspects of mixing, namely **time** and **flow rate**. Therefore two requirements must be introduced into the definition of complete mixing, i.e. we have complete mixing of air within a zone if the following two conditions are met:

1. **Time**: the local mean age of air is at every point in each zone equal to the nominal time constant,
2. **Flow rate**: the local purging flow rate is at every point in each zone equal to the flow rate of outdoor air entering the building.

The first condition is very often satisfied in practice. However, both conditions must be fulfilled and one cannot generally draw the conclusion that if the first condition is satisfied, than the second condition will be met.

Incomplete mixing will show up as different local mean ages from point to point in a zone. The local mean age may both be greater and less than the nominal time constant. Consequently methods based

on the prediction of flow rate by recording the age of air may give rise to both under- or overestimate of the correct flow rate. Incomplete mixing will give rise to a purging flow rate that is less than the flow rate of outdoor air. Therefore methods based on directly recording the flow rate will underestimate the correct flow rate.

3.4. Classification of Tracer Gas Techniques

We can subdivide the different methods into several categories. First, depending on the purpose of the measurement, either the transient techniques or the steady-state techniques can be used *[Sherman, 1990]*.

- the **transient techniques** are used to measure the nominal time constant or the air change rate (or specific flow rate). For that purpose, the tracer is injected in such a way that large changes in concentration are obtained.
- the **steady state techniques** tend to obtain or maintain a quasi-constant tracer gas concentration, in order to estimate directly the air flow rates.

Since, in a single zone, the nominal time constant, τ, and the air flow rate, q, are directly related by:

$$q\,\tau = V \tag{3.1}$$

both techniques could be used to determine either τ or q. However, the error will be larger if the estimation is obtained in an indirect way, because of the errors on the estimation of the volume, V.

Depending on the type of control and injection method we can make the following classification:

- **Decay method.** A suitable amount of gas is injected into the space and mixing is carried out to establish a uniform initial concentration within the zone. The decay of tracer concentration is then used to estimate the air change rate. This is the typical transient technique.
- **Constant injection.** Gas is injected at a constant rate and the time varying concentration response is recorded.
- **Pulse injection.** A short duration gas pulse is injected into the space and the response is recorded.
- **Constant concentration.** Gas is injected into the space under control such that a constant concentration throughout the whole building is maintained. The time varying tracer gas flow rate is recorded.

The constant injection method and the pulse technique are essentially the same methods because there is a direct correspondence between the integrated response from a short release of gas and the equilibrium concentration attained at the same point if the tracer gas were continuously released.

These methods can be further subdivided according to whether or not one single tracer gas or several gases are used, i.e. we have:

- **Single tracer gas methods**
- **Multi tracer gas methods**

If we possess as many tracer gases as there are rooms, then any method can be simultaneously used in all rooms.

The idea behind the constant concentration method is to hide interzonal flows. Therefore, when used in a multizone environment, a single tracer only gives the fresh air ventilation rate into each zone, it does not provide information regarding the flows between rooms.

Single tracer gas techniques may be employed in a multizone network by using a transient technique and making observations at N or more time points *[Bohac and Harrje, 1987]*. This is achieved by applying a method in one room and then repeating the method in the remaining rooms in turn *[Okuyama, 1990], [Mattson, 1990], [O'Neill and Crawford, 1990]*. Although one does not have to wait until the gas has been evacuated before one starts in the next room, such a procedure nevertheless takes quite a long time. Since it is doubtful whether the interzonal flow rates remain constant during the whole period, the use of repeated measurements in a multizone situation is not recommended.

A time varying flow rate poses a further problem in that, under such conditions, not every method gives rise to a correct estimate of the average flow rate. Several methods give rise to a biased estimate of the average air flow rate, because the inverse of an average is generally smaller than the average of an inverse:

$$\frac{1}{\langle c \rangle} \leq \left\langle \frac{1}{c} \right\rangle \tag{3.1}$$

Finally the methods can be sorted according to which type of mathematical method is used to solve the mass flow equations. We can broadly identify two different approaches i.e.:

- **Direct solution of the basic equations or matrix inversion**
- **Integral solution**
- **System identification methods**

Direct solution of the basic equations or matrix inversion means that the system of mass balance equations are solved for the flow rates by a standard numerical method.

To obtain an integral solution, the basic equations are first integrated over a period of time, then solved, giving an average result.

When a system identification method is used, the mass conservation equation is regarded as a state equation and the unknown flow rates are the coefficients in the state equation. Statistical estimation theory based on weighted least square or bayesian methods (see Appendix 2) are used to obtain the flow rates. The estimation errors are also evaluated (see Appendix 3) .

There is an obvious tradeoff between single and multi-tracer gas methods in multizone networks. With a multi-tracer method the measurements may be more straightforward, however, the instrumentation becomes more complicated.

3.6. Summary

The different tracer gas techniques can be broadly divided into two categories; these are steady-state methods, which directly measure the flow rate, Q, and transient methods which measure the nominal time constant, τ_n, or the air change rate, n. The steady-state techniques are based on recording steady-state concentrations or concentrations integrated over a long time, while transient methods are based on recording the change in tracer gas concentration. The different tracer gas techniques and their properties are tabulated in table 3.1 and table 3.2 below.

Tracer injection strategy	Direct result	Cost
Pulse injection	$Q^{\dagger}$	Moderate
Decay	n or τ_n	Moderate
Constant injection rate	$Q^{\dagger}$	Moderate
Constant concentration	Q	Relatively high

†: the volume has no influence only when the air flow rate, Q, is constant.

Table 3.1: Summary of different injection strategies

If air flow varies with time, only the two-point decay and the constant concentration give a correct estimate of the average flow. The constant injection method underestimates the average flow rate if the integration time is much longer than the period of flow variation.

As far as single-zone measurement are concerned, the following conclusions can be stated *[Sherman, 1990]*:

- It appears that decay, pulse and step-up methods require the least measurement time and usually the least preparation. However, with the exception of the two-point decay method, they give a biased estimate of a variable air change rate. These biases remain small if the measurement period is limited to times close to the nominal time constant.
- The long-term integral method, generally used with passive sources and samplers, also gives a biased estimate of the average air flow rate. Since the measurement time is larger, the bias may not be negligible. This technique, however, provides an unbiased estimate of the average tracer concentration. If the tracer is used to simulate a contaminant, such experiments are of great interest for indoor air quality studies.
- The constant concentration technique is accurate and gives an unbiased estimate of the average air flow rate, but it requires the most equipment.

- The constant injection used with long term direct solution is simpler to use and may give, under certain conditions, unbiased estimates of an average air flow rate (see Section 4.3.1).

The two-point decay method, and more generally the multizone, transient methods may lead to unacceptably large uncertainties if the measurement time period is inappropriate. For example, see Section 4.6 for the two-point decay and *[Enai, Shaw and Reardon, 1990]* for two-zone, two-tracer, step-up and decay methods.

#	Method name	Tracer injection technique	Interpretation method	Suited for unbiased average	Suited for continuous record
	Transient methods (tracer gas concentration changes)				
1	(Simple) decay	Decay	Identification	No	No
2	Two point decay	Decay	Integral	Yes	(Yes)
3	Step-up	Constant rate	Identification	No	No
4	**Steady-state methods** (tracer gas concentration is nearly constant)				
5	Pulse	Pulse	Integral	No	(Yes)
6	Constant injection	Constant rate	Direct solution	Yes†	No
7	Long term integral	Any	Integral	No	No
8	Constant concentration	Constant concentration	Integral	Yes	Yes

†: under condition (see Section 4.3.1)

Table 3.2: Summary of single-zone methods [from Sherman, 1990]

Tracer injection strategy	Unbiased average of time varying flow	Well suited for continuous record
Single tracer *(Repeated measurements)*		
Pulse injection	No	No
Decay	No	No
Constant injection rate	No	No
Constant concentration	Yes	No
Multi tracer		
Pulse injection	No	No
Decay	Yes*	No
Constant injection rate	No	Yes
Constant concentration	Yes	Yes

* Only for a two-point estimate

Table 3.3: Summary of multizone methods

4. Treatment of Results

4.1. Procedure

The basic equations presented in chapter 2 are instantaneous equations. This means that, in principle, the flow rates can be determined directly from instantaneous measurements of the tracer injection flow rates, their concentration and the time derivatives of these concentrations.

Using tracer gas monitoring instruments, measurements are usually performed in the following way:

- At a time t_0, an air sample is taken and analyzed. This analysis takes a period Δt_a.
- With constant injection (CITG) and constant concentration (CCTG) tracer gas techniques, the amount of tracer gas necessary to raise the concentration to a target level is injected into the zone at the time $t_0+\Delta t_a$. This amount can be released by opening a valve for a time period Δt_{inj}.
- After injection, a period of time, Δt_{mix}, is allowed for mixing.
- Following the mixing period, the above sequence is repeated.

With some CCTG instruments (e.g. the EMMARA, see Section 6.3.2), the air is continuously sampled and stored, and the injection rate of the tracer is continuous. At periodic time intervals, the stored sample is analyzed and the injection flow rate is changed accordingly.

With all methods, the sampling-analysis-injection-mixing cycle lasts a specific period of time. This time interval is usually the period Δt between two records of measured data. The result of the measurements is therefore a discrete database and the basic equations are continuous. The first step of the interpretation procedure is to take this discretization into account, either by using finite differences instead of the derivatives, or by integration of the equations over the time period Δt. This step leads to a system of linear equations which is solved using well known techniques.

In this chapter, all the variables (except the volumes of the zones) may depend on time but it is implicitly assumed that they are constant or vary linearly during the measurement time interval. This assumption seems obvious, since we have no information of the variation of these variables during the measurement intervals. Nevertheless, it should be remembered that the time step may be large (e.g. 10 minutes) when compared to the time constants of the possible changes of the air- and tracer injection flows. Because of this, interpretation errors may occur, which generally overestimate the air flow rates.

4.2. Discretization and Integration

4.2.1. Time Derivatives and Finite Differences

The basic equations given in chapter 2 contain several time derivatives. These equations can be solved at each time interval, by using finite differences. Either the backwards derivatives:

$$\frac{c_{ik}(t)}{dt} = \frac{c_{ik}(t) - c_{ik}(t-\Delta t)}{\Delta t} \tag{4.2}$$

$$\frac{T_i(t)}{dt} = \frac{T_i(t) - T_i(t-\Delta t)}{\Delta t} \tag{4.3}$$

or the forward derivatives:

$$\frac{c_{ik}(t)}{dt} = \frac{c_{ik}(t+\Delta t) - c_{ik}(t)}{\Delta t} \tag{4.4}$$

$$\frac{T_i(t)}{dt} = \frac{T_i(t+\Delta t) - T_i(t)}{\Delta t} \tag{4.5}$$

may be used. For causality reasons, equations (4.4) and (4.5) may be better. This procedure transforms the basic differential equations into a linear system of equations.

4.2.2. Integration

In practice however, the noise linked with any measurement leads to big uncertainties in the value of the derivatives, and it is recommended to average the measurements over a certain period of time. An integration time equal to one or more measurement interval(s) is preferred. The integration minimizes the effect of experimental errors and will be the only method presented below.

The time average of a variable, $x(t)$, over a period of time, Δt, is, by definition:

$$\langle x \rangle = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} x(t)\, dt \tag{4.6}$$

4.3. Solutions of the Integrated Basic Equations, Single Tracer

4.3.1. Single Zone Measurements

General solution

Equation (2.46) can theoretically be solved by:

$$q_{10} = \frac{T_0}{T} \left\{ s - V \frac{dc}{dt} \right\} \frac{1}{\Delta c} \tag{4.7}$$

but, since concentration, temperature and volume measurements always contain random errors, it is numerically more accurate, to integrate the measurements during a time period, Δt, which is equal to one or more measuring intervals:

$$\int_{t}^{t+\Delta t} q_{10}\, dt = \frac{T_0}{T} \int_{t}^{t+\Delta t} \frac{s}{c-c_0}\, dt - V \int_{t}^{t+\Delta t} \frac{dc}{\Delta c} \tag{4.8}$$

Hence:

$$\int_{t}^{t+\Delta t} q_{10}\, dt = \frac{T_0}{T} \int_{t}^{t+\Delta t} \frac{s}{c-c_0}\, dt + V \{\ln[\Delta c(t)] - \ln[\Delta c(t+\Delta t)]\} \tag{4.9}$$

where ln is for the neperian logarithm. Dividing both sides by Δt finally gives:

$$\langle q_{10} \rangle = \frac{T_0}{T} \left\{ \left\langle \frac{s}{c_1 - c_0} \right\rangle - \frac{V}{\Delta t} \ln \left(\frac{\Delta c(t)}{\Delta c(t+\Delta t)} \right) \right\} \tag{4.10}$$

The tracer gas concentration can also be predicted using:

$$\Delta c(t) = \int_{-\infty}^{t} \frac{s(t')}{V} \exp \left(\int_{t}^{t'} \frac{dt''}{\tau_n(t'')} \right) dt' \tag{4.11}$$

where τ_n is the nominal time constant. If the air flow rate, q_{10}, is assumed to be constant during the measurement, for $0 \le t' \le t$, equation (4.11) becomes:

$$\Delta c(t) = \Delta c(0) \exp\left(\frac{-t}{\tau_n}\right) \int_{0}^{t} \frac{s(t')}{V} \exp \frac{-(t-t')}{\tau_n}\, dt' \tag{4.12}$$

Equation (4.10) is used for the integral interpretation method, while equation (4.12) is the model used to identify (e.g. by regression) the unknown parameters τ_n, $c(0)$, and sometimes even the volume, V. It is important to remember that the identification methods assume a constant air change rate during the measurement.

The general solutions given above can be simplified when some particular injection strategy are used. These are given below:

Decay method, identification technique

In decay measurements, $s = 0$, and equation (4.12) simply becomes:

$$\Delta c(t) = \Delta c(0) \exp\left(\frac{-t}{\tau_n}\right) \tag{4.13}$$

and can be linearized by taking the logarithms of both terms:

$$\ln\left[\Delta c(t)\right] = \ln\left[\Delta c(0)\right] - \frac{t}{\tau_n} \tag{4.14}$$

Linear regression or bayesian techniques (see Appendix 3) can be used together with equation (4.14) to determine τ_n and $\Delta c(0)$ from several measurements of the concentration difference, $\Delta c(t)$ at various times, t. Since this technique assumes a constant ventilation rate, the estimate is unbiased only in this case.

Decay method, integral technique

When $s = 0$, and using the definition of the air change rate, $n = q_{10}/V$, equation (4.10) simplifies and gives an unbiased estimate of an average air change rate $\langle n \rangle$ between two concentration measurements, one at time t and the other Δt later:

$$\langle n \rangle = \frac{T_0}{\Delta t\, T} \left\{ \ln\left[\frac{\Delta c(t+\Delta t)}{\Delta c(t)} \right] \right\} \tag{4.15}$$

This technique is known as the **container method** *[ASTM E 741-83]*. Note that it is not necessary that the decay be exponential or that the flow rate remains constant during the measurement. However, the concentration at time $t+\Delta t$ should be small enough but not too low, in order to avoid large uncertainties. In this case, this uncertainty is calculated by *[Sherman, 1990]:*

$$\frac{\delta n}{n} = \frac{\delta(\Delta c)}{\Delta c(t)} \frac{1}{n\,\Delta t} \sqrt{1 + \exp(2n\Delta t)} \tag{4.16}$$

where $\delta(\Delta c)$ is the uncertainty on the tracer gas concentration (see also Fig. 4.2, Section 4.6). In equation (4.16), it is assumed that the uncertainty on the time is negligible, which is usually the case. The uncertainty on the air change rate is minimum when the measurement time period, Δt, is approximately equal to the nominal time constant. In this case:

$$\frac{\delta n}{n} \approx 3 \frac{\delta(\Delta c)}{\Delta c(t)} \tag{4.17}$$

Since less measurement points are used for that technique than in the identification techniques, this minimum uncertainty is larger that the uncertainty obtained with the identification techniques, as far as the air change rate remains constant. Such is the price for having an unbiased average in case of varying ventilation. The accuracy could however be improved by taking more measurement points, interpreting them two by two using equation (4.15) and averaging the obtained results.

Other possible interpretation methods for decay techniques are described together with the techniques presented above in the literature *[e.g. Sherman, 1990]*. They are however not described here since they neither are simpler nor provide more accurate results.

Pulse injection

If a volume v of tracer is injected in a short pulse at time t, the duration of the pulse being much smaller than the nominal time constant of the room, equation (4.9) becomes:

$$\langle q_{10} \rangle = \frac{T_0}{T} \left\{ \frac{v}{\Delta t\, \Delta c(0)} - \frac{V}{\Delta t} \ln\left[\frac{\Delta c(t)}{\Delta c(t+\Delta t)} \right] \right\} \tag{4.18}$$

and this equation could be used to measure the air flow rate. However, the precision on the measurement of $c(t)$ is very poor, because the tracer cannot be immediately well mixed. Therefore the

integral interpretation is recommended.

Pulse integral technique

The tracer gas concentration is measured before, during and after its injection, until it decays. Using the integral mean value theorem, an estimate of the air flow rate can be obtained *[Axley and Persily, 1988]*:

$$q(\xi) = \frac{T_0}{T} \quad \frac{v - V\,[\Delta c(t+\Delta t) - \Delta c(t)]}{\int_t^{t+\Delta t} \Delta c(t')\,dt'} \qquad \text{with} \qquad t \le \xi \le t+\Delta t \tag{4.19}$$

The term $\Delta c(t+\Delta t) - \Delta c(t)$ may be zero if the initial concentration is zero and if the decay is completed at the end of the measurement. However, it is kept in the equation to allow for shorter measurement periods. The dose (or integrated concentration) can be either calculated by any usual method on the basis of recorded concentrations versus time, or directly obtained experimentally, using grab- or passive sampling.

Constant injection, step-up technique

The concentration is measured just before and after starting the constant injection of tracer gas. If the injection rate is constant, equation (4.12) becomes:

$$\Delta c(t) = \left[\Delta c(0) - \frac{s}{q} \right] \exp \frac{-\tau}{\tau_n} + \frac{s}{q} \tag{4.20}$$

Equation (4.20) was used together with an identification technique to estimate the specific air flow rate, n, and possibly the effective volume, V *[e.g. Sherman, Grimsrud, Condon and Smith, 1980]*.

Constant injection, steady state

However, most users of this technique wait until the exponential term decays nearly completely. Then:

$$\Delta c(\infty) = \frac{s}{q} \qquad \text{and} \qquad q = \frac{s}{\Delta c(\infty)} \tag{4.21}$$

This direct solution gives the correct answer if the air flow rate is constant. Otherwise, the average of several air flow rates obtained on the basis of several tracer gas concentration measurements is an unbiased estimate of the average air flow rate if *[Sherman, 1990]*:

$$\ln[\Delta c(t+\Delta t)] - \ln[\Delta c(t)] \ll n\,\Delta t \tag{4.22}$$

Constant injection, long term integral

With passive samplers (see Sections 5.3.3 and 6.5.4), the average concentration over a large period of time is directly measured. In this case, equation 4.21 is used with an average concentration at the denominator:

$$q = \frac{s}{\langle \Delta c \rangle} \tag{4.23}$$

In this case, q is a biased estimate of the average air flow rate, this estimate being lower than the true value.

Constant concentration

Provided the concentration remains exactly constant throughout a constant concentration measurement, equation (4.10) becomes:

$$\langle q_{10} \rangle = \frac{T_0}{T} \left\{ \frac{\langle s \rangle}{\Delta c} \right\} \tag{4.24}$$

However, in order to correct the results for slight variations in concentration, equation (4.10) may nevertheless be preferred.

4.3.2. Multizone Decay Measurements

Several methods of interpreting the results of single tracer multizone decay measurements were compared *[Riffat, 1989/2]*, and it was shown that the method described in *[Littler, Martin Prior, 1984]* was the most accurate for this case. This technique is as follows:

Assuming a constant, homogeneous indoor air temperatures and introducing the air change rate matrix $\underline{\underline{G}}$, the basic equation (2.33) with $\underline{S} = \underline{0}$ can be rewritten:

$$\underline{\underline{G}} = -\underline{\underline{M}}^{-1}\,\underline{\underline{Q}} \tag{4.25}$$

If $\underline{C}$ is the vector containing the concentrations of the single tracer in the various zones, then equation 2.33 becomes:

$$\frac{d}{dt}\underline{C} = \underline{\underline{G}}\,\underline{C} \tag{4.26}$$

A discrete time model can be deduced from (4.26), which is:

$$\underline{C}(t+1) = \underline{\underline{D}}\,\underline{C}(t) \tag{4.27}$$

where

$$\underline{\underline{D}} = \exp(\underline{\underline{G}}) = \underline{\underline{I}} + \underline{\underline{G}} + \underline{\underline{G}}^2/2! + \underline{\underline{G}}^3/3! + \ldots \tag{4.28}$$

from which the matrix $\underline{\underline{G}}$ can be deduced from the measurement of N+1 vectors $\underline{C}(t)$.

4.3.3. Multizone Identification Methods

Several methods are presented in the literature proposing various injection strategies of a single tracer into several zones. Assuming that the air flow rates remain constant during the time period needed for their determination, they use the least square identification method to fit the parameters of a multizone model on the measurements of time series of tracer gas concentration and injection flow rates.

[Hedin, 1989] and *[Mattson, 1990]* propose to inject the tracers at "constant" flow rate, these changing from time to time in the various zones in order to obtain enough equations. The model used is based on equation 2.7, rearranged as:

$$S_{ik} = m_i \frac{dC_{ik}}{dt} - \sum_{j=0}^{N} (C_{jk} - C_{ik})\, Q_{ij}\,(1-\delta_{ij}) \tag{4.29}$$

and the air flow rates are determined by minimizing the sum of the squared difference between the measured injection rates, S_{ik}, and those calculated using equation (4.29).

[Okuyama, 1990] injects periodic pulses of tracer gas. The period is the same in all the zones, but each zone has a different injection time and duration. A general, sophisticated identification method, also using least square fit on the multizone infiltration model, is used, allowing, in principle, the determination of any unmeasured parameter. An apparatus, based on that method is built and measurements are shown in five-zone and nine-zone buildings. A few hours are needed to obtain a stable estimate of the air flow rates.

An error analysis is presented and tests in a five-zone test house showed an agreement within 20 % with the true air flow rates.

[O'Neill and Crawford, 1989 and 1990] have injected successive single tracer pulses in each zone. Their least square fit method is based on the equation (2.33), which is discretized in a way similar to the way described in Section 4.3.2, but with the injection vector $\underline{S} \neq \underline{0}$:

$$\underline{C}(t+\Delta t) = \underline{\underline{A}}\,\underline{C}(t) + \underline{\underline{B}}\,\underline{S}(t) \tag{4.30}$$

where $\underline{\underline{A}}$ is defined by

$$\underline{\underline{A}} = \exp(-\underline{\underline{G}}\,\Delta t) = \underline{\underline{I}} - \underline{\underline{G}}\,\Delta t + (\underline{\underline{G}}\,\Delta t)^2/2! - (\underline{\underline{G}}\,\Delta t)^3/3! + \ldots \tag{4.31}$$

and:

$$\underline{B} = \int_0^{\tau+\Delta t} \exp(-\underline{G}\, t)\, \underline{M}^{-1}\, dt = [\underline{I}\, \Delta t - \underline{G}\, \Delta t^2/2! + \underline{G}^2\, \Delta t^3/3! + \ldots]\, \underline{M}^{-1} \qquad (4.32)$$

The parameters (e.g. air flow rates and effective volumes) are identified by minimizing the sum of the squared differences between the concentration vector measured at time $t+\Delta t$ and the vector calculated using equation (4.30) and the observations at time t.

A three zone test house was measured this way and the effective volumes and air flow rates were determined within less than 3 hours with an accuracy of 3 % for the volumes and 15 % for the air flow rates.

4.4. Solutions of the Integrated Basic Equations, Multi-Tracer

Several simplified solutions, valid for decay experiments , can be found in the literature, e.g. *[Sinden, 1978], [L'Anson, 1982]. [Irwin and Edwards, 1989]* have compared several such methods and claim that their simplified solution, based on the work of *[Dick, 1949 and 1950]* gives the closest fit to site measurements, even when the concentration decay is perturbed by fluctuations.

The methods presented below are more general and useable for any tracer injection strategy.

At each measurement time interval, the measurements give discrete values of the concentrations, C_{ik}, and injection flow rates, S_{ik} (i, k = 1 to N). From these and the knowledge of the air masses, M_i, in each zone, the mass flows, Q_{ij}, can be computed. In addition, the volume flows, q_{ij}, can be computed from the volume, V_i, of each zone, the volume concentrations, c_{ik}, the temperatures, T_i, and the injection flow rates, s_{ik}.

In equation (2.5) or (2.7), the zone, i, and the tracer, k, vary independently from 1 to N. Hence there is a system of N^2 equations which, when combined with the system of N equations, (2.1), enables the N^2+N unknowns, q_{ij}, to be found. Two methods of solution, corresponding to the two presentations of equations given in Section 2.4 are presented below.

4.4.1. Zone by Zone Systems of Equations

This method will be presented in terms of volume flows, and is based on the systems of equations (2.28). These are an assembly of N independent sub-systems containing the equations for each given zone, i. Each sub-system may be written in a matrix form *[Roulet, Compagnon, 1989]*:

$$\underline{y}_i = \underline{c}_i' \, \underline{x}_i' \qquad (4.33)$$

where $\underline{y}_i$ is the vector having N components y_{ik}:

$$y_{ik} = \frac{V_i}{T_i} \frac{dc_{ik}}{dt} - \frac{s_{ik}}{T} \qquad \text{where } k \text{ varies from 1 to N} \qquad (4.34)$$

Note: usually $s_{ik} = 0$ if $i \neq k$, since only gas i is injected in zone i. In the case of the constant concentration technique, the time derivative of the concentration c_{ii} of tracer i is also zero in zone i (where it is injected). This assumes that the injection rate of the tracer gas is perfectly controlled.

$\underline{x}_i'$ is the vector containing the $N+1$ unknown flows into zone i:

$$\underline{x}_i' = (q_{0i}, q_{1i}, \ldots, q_{i-1,i}, 0, q_{i+1,i}, \ldots, q_{Ni}) \qquad (4.35)$$

and $\underline{c}_i'$ is a matrix containing the element, Δc_{kj}, in row k and column j:

$$\Delta c_{kj} = \frac{c_{jk} - c_{ik}}{T_j} \qquad (4.36)$$

The matrix, $\underline{c}_i'$, has N rows and $N+1$ columns, but the column, i, is filled with zeros. The vector, $\underline{x}_i$, has also $N+1$ components, the component i, corresponding to q_{ii} being zero. We can therefore contract the system (4.16) into:

$$\underline{y}_i = \underline{c}_i \, \underline{x}_i \qquad (4.37)$$

where $\underline{x}_i$ is the vector $\underline{x}_i'$ without the component i, and $\underline{c}_i$ is the matrix $\underline{c}_i'$ without the column i. The system (4.37) is then entirely determined if the matrix $\underline{c}_i$ is not singular.

At this stage, the following averaging procedure is recommended:

Equation (4.37) is integrated over a time period Δt during which it can be assumed that the air flows, q_{ij}, and temperatures, T_i, (or the mass flows, Q_{ij}) remain constant. This time period is generally equal to the measurement interval, and is typically 5 to 15 minutes.

A new system of equations is then obtained for each zone, i, where each line corresponds to a tracer gas, k, and each column to an adjacent zone, j, the first one being the outside:

$$\langle \underline{y}_i \rangle = \langle \underline{c}_i \rangle \langle \underline{x}_i \rangle \tag{4.38}$$

where:

$\langle \underline{x}_i \rangle$ is the vector of the average unknown air flow rates leaving zone i;

$\langle \underline{y}_i \rangle$ is the matrix with the elements:

$$\langle y_{ik} \rangle = \frac{1}{\Delta t} \int_t^{t+\Delta t} T_i \, y_{ik} \, dt = \frac{V_i}{\Delta t} [c_{ik}(t+\Delta t) - c_{ik}(t)] - \frac{T_i}{T} s_{ik} \tag{4.39}$$

$\langle \underline{c}_i \rangle$ is the concentration matrix with elements:

$$\langle \Delta c_{kj} \rangle = \frac{1}{\Delta t} \int_t^{t+\Delta t} T_i \, \Delta c_{kj} \, dt = \frac{T_i}{T_j} \frac{1}{\Delta t} \int_t^{t+\Delta t} [c_{jk} - c_{ik}] \, dt \tag{4.40}$$

The last term in equation (4.40) contains the average concentrations in each zone. Since these concentrations are measured at discrete time intervals, the integral should be approximated with a sum, hence:

$$\langle \Delta c_{kj} \rangle = \frac{T_i}{2 \, T_j} [c_{jk}(t+\Delta t) + c_{jk}(t) - c_{ik}(t+\Delta t) - c_{ik}(t)] \tag{4.41}$$

Finally, the system (4.38) may be solved using:

$$\langle \underline{x}_i \rangle = \langle \underline{c}_i \rangle^{-1} \langle \underline{y}_i \rangle \tag{4.42}$$

The relation (4.42) gives all the flows entering zone i. Using (4.42) for each zone gives all the air flows, except the air flows going outdoors. These are obtained using equations (2.29).

It is interesting to note that the components of the vector $\langle \underline{y}_i \rangle$ have the unit of air flow rates, and may be called "gross air flow rates". As it is shown in equation (4.38), they are a linear combination of the air flow rates coming into zone i, the coefficients being the elements $\langle \underline{\Delta c}_{kj} \rangle$. This fact is much more interesting than it appears at first, as will be shown later (Section 4.5.3).

4.4.2. Global System of Equations

As shown in § 2.4.1, all the tracer conservation equations are taken together in a single system, which is, in terms of mass flows:

$$\frac{d}{dt} [\underline{\underline{M}} \, \underline{\underline{C}}] + \underline{\underline{Q}} \, \underline{\underline{C}} = \underline{\underline{S}} \tag{2.5}$$

where each row of these $N \times N$ matrices corresponds to a zone and each column to a given tracer gas. All unknown flow rates are included in the flow matrix, $\underline{\underline{Q}}$. Since, as usual in multi-tracer measurements only one tracer is injected into each zone and therefore, it can be indexed with the same subscript as the zone. In this case, and if the tracer is well mixed in the zone, the largest elements of the matrix $\underline{\underline{C}}$ are on the diagonal and then $\underline{\underline{C}}$ has an inverse matrix, $\underline{\underline{C}}^{-1}$.

Equation (2.5) can be integrated over the time period Δt to give:

$$\int_t^{t+\Delta t} \frac{d}{dt} [\underline{\underline{M}} \, \underline{\underline{C}}] \, dt + \int_t^{t+\Delta t} \underline{\underline{Q}} \, \underline{\underline{C}} \, dt = \int_t^{t+\Delta t} \underline{\underline{S}} \, dt \tag{4.43}$$

and an average air flow matrix $\langle \underline{\underline{Q}} \rangle$ may be defined using the integral mean value theorem:

$$\int_t^{t+\Delta t} \underline{\underline{Q}}\,\underline{\underline{C}}\,dt = \langle \underline{\underline{Q}} \rangle \int_t^{t+\Delta t} \underline{\underline{C}}\,dt \tag{4.44}$$

This gives:

$$\underline{\underline{M}}(t+\Delta t)\,\underline{\underline{C}}(t+\Delta t) - \underline{\underline{M}}(t)\,\underline{\underline{C}}(t) + \langle \underline{\underline{Q}} \rangle \frac{\Delta t}{2} \left[\underline{\underline{C}}(t+\Delta t) + \underline{\underline{C}}(t)\right] = \Delta t \langle \underline{\underline{S}}(t) \rangle \tag{4.45}$$

Defining the average concentration matrix by:

$$\langle \underline{\underline{C}} \rangle = \frac{1}{2} \left[\underline{\underline{C}}(t+\Delta t) + \underline{\underline{C}}(t)\right] \tag{4.46}$$

and dividing (4.45) by Δt, we obtain the linear equation:

$$\frac{1}{\Delta t} \left[\underline{\underline{M}}(t+\Delta t)\,\underline{\underline{C}}(t+\Delta t) - \underline{\underline{M}}(t)\,\underline{\underline{C}}(t)\right] + \langle \underline{\underline{Q}} \rangle \langle \underline{\underline{C}} \rangle = \langle \underline{\underline{S}}(t) \rangle \tag{4.47}$$

which can be solved by multiplying both sides by $\langle \underline{\underline{C}} \rangle^{-1}$ at the right:

$$\langle \underline{\underline{Q}} \rangle = \langle \underline{\underline{S}}(t) \rangle \langle \underline{\underline{C}} \rangle^{-1} - \frac{1}{\Delta t} \left[\underline{\underline{M}}(t+\Delta t)\,\underline{\underline{C}}(t+\Delta t) - \underline{\underline{M}}(t)\,\underline{\underline{C}}(t)\right] \langle \underline{\underline{C}} \rangle^{-1} \tag{4.48}$$

It should however be remembered here that calculating the inverse of $\langle \underline{\underline{C}} \rangle$ is not the best numerical way to solve the linear system (4.47). Good numerical methods are found in numerous handbooks.

If the temperature inside is uniform and constant, (4.48) simplifies to:

$$\langle \underline{\underline{Q}} \rangle = \left\{ \langle \underline{\underline{S}}(t) \rangle - \frac{1}{\Delta t} \underline{\underline{M}} \left[\underline{\underline{C}}(t+\Delta t) - \underline{\underline{C}}(t)\right] \right\} \langle \underline{\underline{C}} \rangle^{-1} \tag{4.49}$$

This method could give biased results if Δt is larger than the nominal time constants of the measured zones. Therefore, the interval between measurements should not exceed the smallest expected time constant, especially in case of varying air flow rates.

4.4.3. Comparison of the Two Methods of Solution

The global method (Section 2.4.1), looks very attractive and elegant, however, it has several disadvantages when compared with the method described in 2.4.2. These include:

- It is not possible to take explicit account of flows that are obviously zero (i.e. flows between unconnected zones). The solution of the system (4.47) gives values for these flows, which are generally not zero, because of measurement and rounding errors. These figures might even be negative, and hence have no physical meaning. In fact, when compared to the confidence intervals, these flows are not significantly different from zero. *[Sherman, 1988]* proposes a correction method to eliminate these flows a posteriori.
- The complete system (4.47) is often not as well conditioned as zone-by-zone systems. The consequence is a larger uncertainty on the final results (see appendix 2 on error analysis).
- Finally, the global solution needs one tracer gas for each zone or the repetition of the measurement N times under constant air flow conditions but with different tracer concentrations. This may be a problem if there are more than 4 or 5 zones. Using the zone-by-zone method, it is possible to plan the experiment in such a way that much useful air flow information can be obtained (see § 4.5.3).

4.5. Measurements with Fewer Tracers than Zones

There is limited number of possible tracer gases, and analyzers are expensive. Therefore, measurements using more than 3 tracers are rare and the literature does not report measurements with more than 5 tracers. However, there is often more than 3 to 5 zones in a building, and methods exist to get information even when there are fewer tracers than rooms.

4.5.1. Reducing the Number of Zones

By opening connecting doors and using mixing fans, a given tracer may be homogeneously spread in more than one room, and several rooms may be connected into one single zone.

Another method is to use the constant concentration method and to put the same concentration of tracer in each of the rooms which are to be combined. This method works very well with a single tracer. If N rooms of a building are individually controlled at the same concentration of the same tracer, the inter-room flows cannot be measured but all the ventilation flow rates from outside the controlled zone to each room are measured.

In this case, the equation (4.38), rewritten for one tracer, contains one line but the matrix $\langle \underline{c_i} \rangle$ still has as many columns as there are flows coming into the zone i:

$$\langle y_i \rangle = (\Delta c_{10}, \Delta c_{11}, \ldots, \Delta c_{1,i-1}, \Delta c_{1,i+1}, \ldots, \Delta c_{1N}) \begin{pmatrix} q_{i0} \\ q_{i1} \\ \cdots \\ \cdots \\ q_{i,i-1} \\ q_{i,i+1} \\ \cdots \\ \cdots \\ q_{iN} \end{pmatrix} \tag{4.50}$$

Hence it is obvious that when the tracer concentration is the same in all the zones, all the elements, Δc_{kj}, are zero, except Δc_{10} which is the coefficient of the air flows q_{i0} coming from outdoors. Therefore we have simply:

$$\langle q_{i0} \rangle = \frac{\langle y_i \rangle}{\langle \Delta c_{10} \rangle} \tag{4.51}$$

This technique is more difficult to use with several tracers, since all the tracer concentrations in each of the combined rooms of a zone should be the same. That means that not only the tracer injected in that zone but also the tracers coming from the neighboring zone should be controlled. This is why such a technique not to be found in the literature.

Multi-tracer constant concentration is, however, used for two practical reasons; these are:

- if the zones are not too well inter-connected, the infiltration flow rates from outside can be measured even when they are time-dependent;
- the maximum concentration is controlled, which is preferred for reasons of safety.

4.5.2. Repeating the Measurements

If (and only if) the air flow conditions (air flow rates, air densities and temperatures) remain constant during the whole measurement, it is theoretically possible to obtain enough equations with very few tracers (even with only one) by repeating the measurement with different tracer injection flow rates or different tracer concentrations.

Several experiments are given in the literature using one tracer in two or more zones. Most of them are decay measurements *[Perrera and Walker, 1985], [Riffat and Eld, 1988], [Riffat, 1989], [Sandberg and Stymne, 1989]*, and some are constant injection *[Hedin, 1989]* and *[Mattson, 1990]* or pulse injection *[Okuyama, 1990], [O'Neill and Crawford,1990]*.

Here again, the zone-by-zone interpretation method may be used without any problem, by introducing into each equation of the system the results of each measurement. For this purpose, the data corresponding to different tracers are replaced by those of the different measurements.

However this method is restricted to a small number of zones, since the condition number of the resulting systems of equations becomes unpractically large as the number of equations grows. Therefore, identification techniques developed on purpose and adapted to the injection strategy may give better results *[Irwin and Edwards, 1987 and 1989], [Okuyama, 1990], [O'Neill and Crawford, 1989 and 1990], [Okuyama, 1990]*

If the number of measurements (that is the number of measured concentrations) is larger than the number of zones, least square fit identification techniques can be used (see Appendix 3). To improve the condition number of the system of equations, the injection flow rate should be varied in the different zones. Several such techniques are proposed in the literature *[e.g. Okuyama, 1990]*.

4.5.3. Planning the Injection Strategy.

It is common to have a large number of rooms in a building, but they are almost never all connected to each other. Hence, flows which differ from zero are often much less than $N(N+1)$. Using the zone by zone interpretation method, it may be possible to distribute the small number of available tracers in the zones in such a way that all directly connected zones have different tracers. Therefore, it is sufficient to have as many tracers as flows entering a zone, to measure all the possible flows.

For some zones, it may happen that there are fewer entering flows than tracers. In this case, the system (4.42) is over determined but flow rates can still be evaluated, e.g. using a least square fit or a Bayesian technique (see Appendix 3).

When there are fewer tracers (or fewer measurements) than entering flows into a zone, the system (4.42) is under-determined, and the air flows cannot be calculated. However, it is always possible to calculate the "gross air flow rates" $\langle y_i \rangle$ and the coefficients $\langle c_{ij} \rangle$. This information may be very useful, since the gross air flow rates, $\langle y_i \rangle$, are linear combinations of the air flow rates.

For example, gross air flow rates can be used for the evaluation of a multizone infiltration simulation code, which can compute the linear combination from the calculated air flow rates and compare them with the measured $\langle y_i \rangle$.

As an example, let us take a building which has 4 distinct zones. Only three tracers are injected, as shown in Figure 4.1.

With these three tracers, all the air flows rates entering zones 2 and 4 can be obtained. In zones 1 and 3, we can only get 3 linear combinations of the 4 entering air flow rates. Since the inter-zone air flow rates are not all determined, the air mass conservation equation cannot be used to obtain the air flow rates going outdoors.

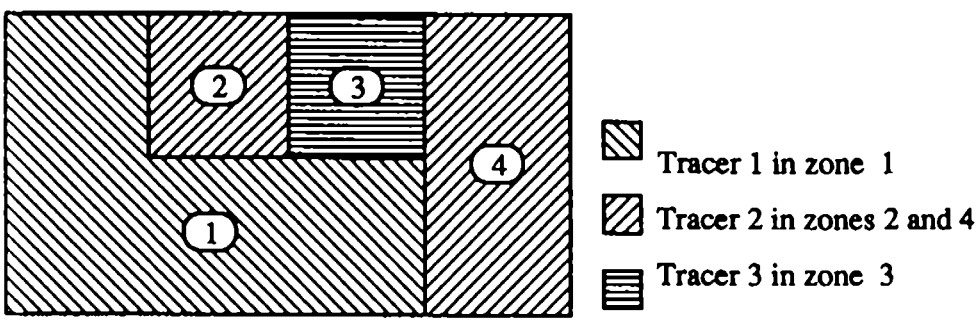


Figure 4.1: How three tracers can be injected in a 4-zone building to determine most of the possible air flow rates.

To summarize, there are not more than 20 air flow rates in a 4 zone building. Since, in this case, the flows Q_{24} and Q_{42} cannot exist, 18 possible flows remain. From the measurements undertaken with three tracers, 6 air flow rates are determined separately, 8 are grouped into 6 independent linear combinations. The last 4 outgoing flows cannot be determined without further measurements.

This example shows clearly the interest of the zone-by-zone interpretation method, which allows one to obtain partial results when there are not enough tracers. The global interpretation method can be applied only for experiments where there are as many measurements as zones.

Finally, alternative measurements (e.g. differential pressure measurements or air speed profiles) may show that some flow rates in the linear combinations are zero. In this case they can be eliminated in these linear combinations and the remaining flows may be obtained.

4.6. Sources of Error, and Error Analysis

The basic measured data in tracer gas measurements are concentrations versus time, room volumes and, for pulse,constant concentration or constant emission methods, injected tracer amounts or flow rates. These data are contaminated with measurement or instrumental errors.

In particular, the perfect mixing assumption is often difficult to achieve, especially in large enclosures. Large and uncontrolled errors may arise if the measured tracer gas concentration is not representative

of the measured zone.

Time can be measured very accurately and therefore, timing errors can usually be neglected. This is especially the case when an automatic data logger is used.

Other measurement errors propagate through the systems of equations, and generally result in larger relative errors in the final results.

To be acceptable, the results must be given together with their confidence intervals. It is recommended to perform the error analysis **before** the measurements, since this analysis provides informations which are essential for the planning of the measurements.

As an example, the Figure 4.2 illustrates the equation 4.16, which gives the relative error on the air change rate or on the nominal time constant. It is clearly seen there that the error may grow in an unacceptable way if the measurement time period is improperly chosen.

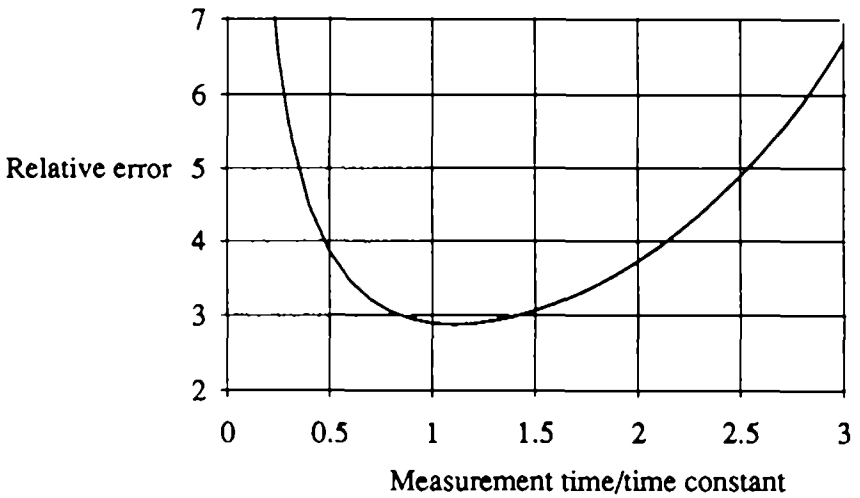


Figure 4.2: Two-point decay technique: ratio of the relative errors on the nominal time constant (or on the air change rate) and the tracer concentration, as a function of the ratio of the measurement time to the nominal time constant.

This error analysis is also useful to choose a technique adapted to the measured object, to the objective of the measurement and to the available material.

Appendix 2 gives more indications on the general methods used to compute the probable errors. For specific techniques, the reader may consult the literature on the topic, in particular:

- A comparison of the air flow rates in a laboratory test house measured by decay and constant concentration tracer gas techniques is presented by *[Sandberg and Blomqvist, 1985]*. Based on a total of 21 tests, the accuracy of the constant concentration technique in predicting the total air flow rate is about 6 %, while the decay technique showed a larger inaccuracy.
- A interpretation methods including error analysis is presented by *[Walker, 1985]* for single- and multi-tracer, multizone decay measurements, together with an application to a test house not inhabited but located in the field. A similar error analysis for other measurement techniques is presented in *[Roulet and Compagnon, 1989]*.
- An analysis of errors associated with passive ventilation measurement techniques *[Sherman, M. 1987]* addresses the bias that passive sampling introduces in the average air flow rate. It introduces the concept of multizone ventilation efficiency and concludes that this technique underpredicts the average air flow rates, but is appropriate for indoor air quality studies. To improve mixing, which is a critical issue, multiple injectors are recommended.
- A detailed calculation of the uncertainty of air flow calculations using multizone, single- and multi-tracer gas measurements is presented in *[Sherman, 1988]*. In this publication, the global system of equations is assumed to be used and examples of the errors obtained using different techniques (multi-tracer with constant injection and as well continuous sampling as integral, passive sampling; and single-tracer, constant concentration) are presented.
- Errors in multizone measurements are addressed in particular by *[Riffat, 1989/2]*, *[Enai, Shaw, and*

Reardon, 1990], and *[Okuyama, 1990]*. The conditioning of the problem is here of great importance. It can be improved by a proper choice of the injection strategy and an optimal timing of the air sampling. On one hand, these strategies can be simulated and the errors predicted before the measurements, thus allowing the best choice. On the other hand, the best timing for sampling depends on the air flow rates themselves, and therefore, the concentrations should be measured at periodic time intervals. During the interpretation procedure, and after a first estimate of the air flow rates, the best sampling times can be determined and used to obtain the best estimates of the flow rates.

5. Components of a Tracer Measurement System

5.1. List of the Components

Any tracer measurement system has the following components (fig. 5.1):

- an **injection system** allowing the injection of controlled quantities of tracer gas(es) at suitable locations in the measured zones of the building,
- a **sampling system**, taking samples of air in the zones to bring them to the analyzer,
- an **analyzer**, measuring the concentration of tracer(s) in the sampled air, and
- a **control system**, controlling all the measurement functions.

The choice of tracer gases depends not only on the components of the system but also on the purpose and the conditions of the measurements (e.g. small or large volumes, inhabited or not, etc.).

In this chapter, these components are discussed in detail, together with their functions. For each component, there are often several choices, each of which are discussed in the following sections.

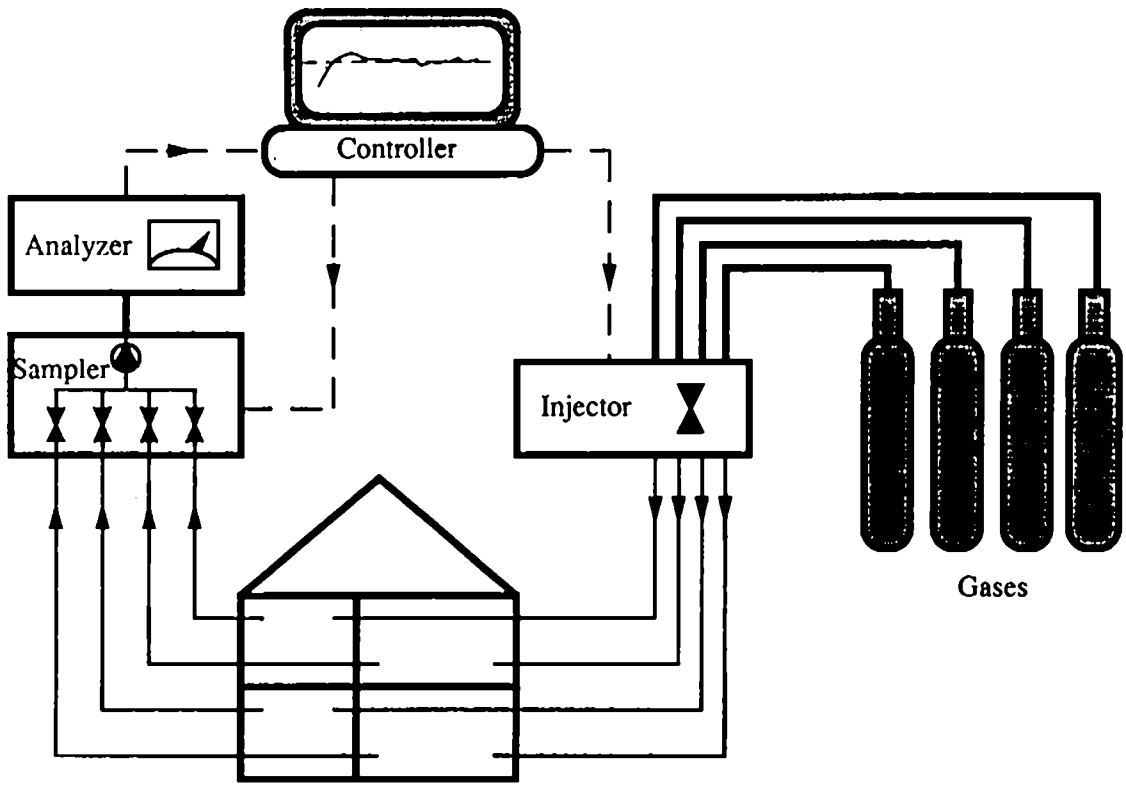


Figure 5.1: Schematics of a multi-tracer measurement system.

5.2. Injection

5.2.1. Purpose of the Injection

The injection system should inject controlled quantities of tracer gas at suitable locations in the building to be measured. Depending on the measurement method used, this quantity of tracer can be injected:

- in one **pulse**, in order to get an initial concentration (e.g., for measurements using the decay or the integral method)
- at a **constant rate** (used mostly in passive injectors together with passive samplers)
- at a **controlled rate** varying with the time, in order to obtain a constant concentration of the tracer in the controlled zone.

The injector may control either the volume flow s or the mass flow S, but it is the latter which should be known. The relation between these flows is:

$$S = \rho s \tag{5.1}$$

where ρ is the density of the tracer gas [kg/m^3] at room temperature. Using the law of perfect gas, this density is:

$$\rho = p M/RT \tag{5.2}$$

where:

- p is the pressure [Pa]
- M the molecular weight [kg/mole]
- R the molar gas constant: $R = 8.31396$ [J/(mole.K)]
- T the absolute temperature [K]

Note that the tracer should always be injected into rooms which have a higher air temperature than the dew point of the diluted tracer. In this case the law of perfect gas is valid.

5.2.2. Types of Injectors

Depending on the type of tracer flow and on the measurement system, several injection systems can be used. These systems are described below.

Supersonic nozzle

If the tracer is delivered through a small orifice at a known flow rate, then, subject to proper calibration, the delivery or injection time is taken as a measure of the injected quantity. If the velocity of the tracer through the nozzle is lower than the speed of the sound, the flow rate depends on the pressure drop through the orifice. This is a problem if the tracer (or a mixture of tracer and air) is not injected directly into the measured zone, but instead, is injected by a pipe. In this instance, the pressure drop through the pipe may affect the flow, thus making the calibration procedure more complicated.

If the velocity of tracer through the smallest section of the nozzle is greater than the speed of the sound, the volume flow rate no longer depends on the pressure drop, but is nearly proportional to the upstream pressure. The pressure drop through the injection network now has no influence on the flow rate. To obtain such supersonic flow, the orifice should be small and the pressure drop should be large. For usual gases, this means that the critical ratio of the upstream pressure to the downstream pressure is approximately 2.

Mass flow controllers

In recent years, mass flow controller devices have become more common place. These devices comprise a mass flow meter, which measures the mass flow with a hot wire (or hot film) anemometer and a feedback loop which controls a needle valve. The mass flow is controlled to within 1% accuracy (full scale) in a 50:1 operating range. Calibration should be performed for each gas, since the response of the hot wire depends on the tracer used. Response time is typically less than 10 seconds.

Volumetric injection

The simplest way to inject a given volume of tracer is to use a calibrated syringe, pumping the tracer at a known pressure into a known volume. This is widely used in manual injection and sampling, and could be automatically achieved using volumetric pumps.

Passive tracer sources

Perfluorocarbon tracers (often called PFT) can be analyzed in minute quantities. An easy way to inject such very small quantities, is to let the tracer permeate through a suitable solid, for example a silicon rubber, or to diffuse through a capillary tube. Such sources are illustrated in Figure 5.2. The capsule contains a relatively large quantity of tracer in liquid form (e.g. 0,4 ml). In the gap between the liquid and the plug, the tracer is gaseous, at a pressure which is equal to the saturation vapor pressure at ambient temperature.

The tracer vapor diffuses through the rubber plug or the capillary tube at a diffusion rate which is dependent on the temperature of the source. Experimentally it was shown *[Dietz, Goodrich, Cote, Wieser, 1984; Dietz, D'Ottavio, Goodrich, 1985]* that the long term change of strength of PFT sources within a temperature range from 20 to 40 °C can be described by the following empirical formula:

$$\frac{q(T)}{q(T_o)} = \frac{\exp(\Delta H/RT_o)}{\exp(\Delta H/RT)} \tag{5.3}$$

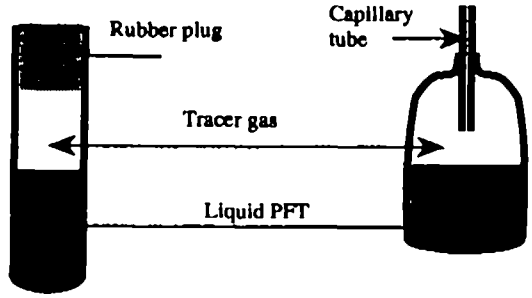


Figure 5.2: Cross section of effusion sources. Left, capsule with a silicon rubber plug [Dietz, Goodrich, Cote, Wieser, 1984; Dietz, D'Ottavio, Goodrich, 1985]. Right, glass capsule with a capillary tube [Stymne, NSIB Gävle, personal comm.]

For rubber sealed capsule, according to *[Dietz, Goodrich, Cote, Wieser, 1984]*, the activation energy ΔH for long term (10 days) variations is 35 ± 5 kJ/mole for PDCH, 33 ± 5 kJ/mole for PMCH and 30 ± 5 kJ/mole for PDCB†. On average, the long term activation energy is 33 ± 5 kJ/mole for common PFTs. For short term variations, the activation energy is about 25 ± 5 kJ/mole for PDCH and 15 ± 2 kJ/mole for PDCB. This difference between short and long time activation energy occurs because temperature changes and the corresponding tracer pressure in the cap and diffusion coefficient change quickly, but a period of time is needed to change the PFT concentration in the rubber plug (see appendix 1). This phenomena does not occur in capillary sources.

The result is that, at ambient temperature (that is T = 293 K), the change in strength is about 5% per degree for long term temperature changes. Hence it is recommended to operate these diffusion sources at constant temperature.

Depending on the tracer used and on the dimensions of the diffusive plug (or the length and diameter of the capillary tube), flow rates from 0,3 to 10 µl/h are obtained and, since the stored tracer inside the cell is liquid, the cells may have a lifetime of several years.

Each source should be engraved with an identification code, identifying the PFT type and the source itself. The sources are usually deployed one per every 50 m^3 of living area. Typically, in a single dwelling, two sources are placed in the living room - dining room - kitchen area and one in each of the bedrooms. The same type of source should be used if the floor is to be treated as a single zone. Alternatively, the dwelling can be divided into two zones, the family zone (living room - dining room - kitchen) and the bedroom zone (the bedrooms, bathroom and hall), each tagged with the appropriate number of PFT sources but of different types.

The sources are used as received; they are always emitting tracer, there is nothing to open or uncover, and they may be placed in any orientation. Generally, a PFT source is placed within 0.5 to 1.5 meters of the floor and no closer than 1 m to an outside wall. For example, it can be taped to the leg of a table or even on a lower portion of a hanging chandelier. Since the source is sensitive to temperature, it should not be placed within a meter of a heating or cooling source, in direct sunlight or other drafty location such as a window, nor at a location where air would carry the PFT vapors outside or to another zone before they had mixed uniformly within the zone where they were placed. Since heated air rises and cooled air sinks, the PFT source should be at a vertical location not too far above or below the temperature measurement/control elevation, and should not be placed above a warm air source (e.g., a lamp or the top of a refrigerator) not below a cooled air source (e.g., an air conditioner vent or a window sill). The average temperature of the source must be recorded. Note: the daily average room temperature is usually adequate for this purpose, even in the case of one or more daily temperature set-back cycles.

5.2.3. Calibration of the Tracer Gas Injector

Except for the decay method, the tracer gas injection flow rate must be known to a high degree of

† PDCH, PMCH and PDCB are typical PFT tracers which are described in Section 5.6.

accuracy. Therefore, the injectors should be calibrated to ensure that the desired quantity of tracer is delivered. This calibration is performed by measuring the flow from the injector using another flow measurement method. The injector should be calibrated with the tracer used.

Various flow meters may be used for calibrating the injectors. Most of them are presented in Part II, Section 3.2. The choice of the most appropriate flow meter depends on the tracer flow rate, the required accuracy, the possible interactions of the tracer with the calibration meter, the cost and the availability of the flow meter.

For small flow rates, the most used methods are:

- weighing the tracer container when injecting (II, § 3.2.2)
- using a gasometer or a rotating cylinder gas flow meter (II, § 3.2.3)
- using a soap bubble flow meter (II, § 3.2.4)
- using a rotameter (II, § 3.2.4)

The best method to calibrate passive effusion cells, is to weigh them accurately, to maintain them at a constant temperature for a period and to weigh them again. This gives a direct measure of the mass flow rate. The time between the weighing must be large enough to ensure accuracy. If the balance has an accuracy of ± 1 µg, a loss of at least 100 µg should be measured. Such loss can take between 10 and 300 hours, depending on the measured source.

If the injector is time-controlled, that is if the injected quantity is controlled by opening a valve for a given period of time, the linearity must also be confirmed. Ideally 10 injections of 1 second should give the same amount of tracer as 1 injection of 10 seconds. If it is not the case, a calibration curve giving the flow rate versus the injection time should be prepared.

Special care should be taken if the tracer gas is soluble in the liquid contained in some flow meters (e.g. gasometers). For example, nitrous oxide is very soluble in most usual liquids such as water, alcohols, oils, alkanes, etc. When tracer gas is soluble, the solution must first be saturated with the tracer, and the calibration must be conducted at constant temperature.

5.2.4. Mixing Tracer Gases in the Zone

Perfect mixing of tracer gas in the air of the measured zone is always assumed when determining the air flow rates. It is therefore important to ensure that the injected zone well mixed with tracer. Several methods can be used for this purpose.

Mixing fans

The most widely used method to ensure perfect mixing is to inject the tracer upwind of a mixing fan, which can be a small 30 W cooling fan used in the electronic industry. Alternatives include portable oscillating fans or "room extract" fans. This methods works perfectly but changes the thermal gradients in the measured zone, and may affect the air exchange rates.

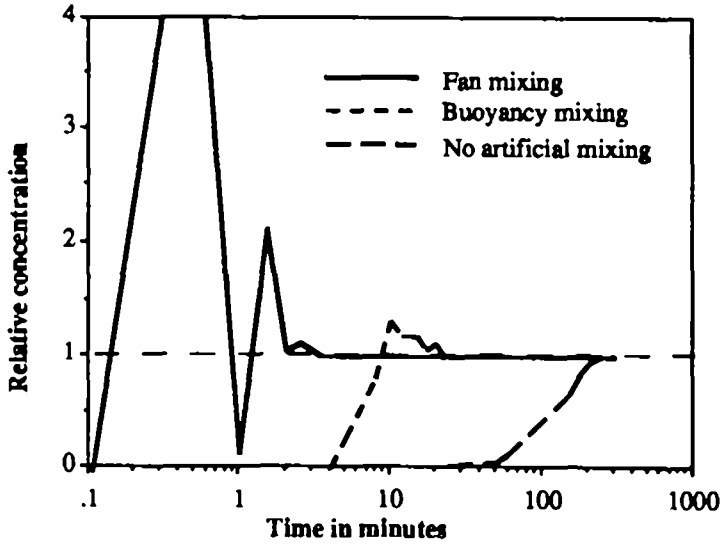


Figure 5.3: Evolution of mixing in an room. Note the logarithmic time scale. [Compagnon, Fürbringer, Jakob, Roulet, 1991].

In some circumstances mixing fans may be avoided by placing the ends of the injection pipes at the locations where natural convection or mechanical ventilation provide significant air currents. Moreover, avoiding pulses of tracer greatly assists the attainment of a uniform tracer gas concentration and therefore, a continuous injection flow rate is preferred.

Figure 5.3 shows the concentration at the center of a 3.5 x 4 x 2.7 m controlled, isothermal and airtight room versus time after an injection pulse in an upper corner and with various mixing systems. The mixing fan is a small fan as shown in Figure 5.4, located downstream the injection pipe. The buoyancy mixing was caused by a 100 W electric bulb located just under the injection pipe, at mid-height. Note that even without mixing, in an isothermal room, the concentration becomes stable and uniform after only 4 hours.

Injection jets

Good mixing with the air around the injection port is obtained if the speed of the tracer gas at the injection outlet is large enough to create a turbulent jet. For this purpose, the flow controlling valve and nozzle should be at the end of the injection tube, with the tube maintained under pressure. It is noted, however, that these two conditions complicate the experimental arrangement since control leads must extend to the end of the injection tube, and, because the whole network is under pressure, the system will be more sensitive to leaks.

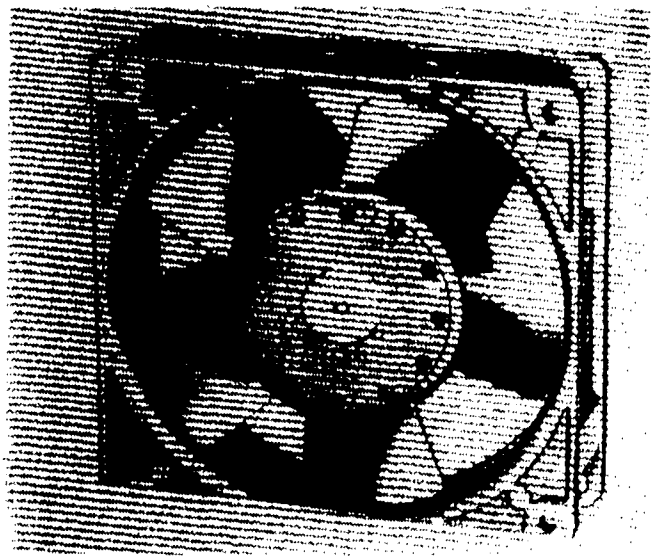


Figure 5.4: Example of mixing fan.

Manual injection into large volumes

In buildings with a large internal volume it may be necessary to discharge large amounts of tracer. If this is the case, then the following method may be used: the operator works out a zig-zag or circular path through the area which will give good coverage of the building. The time taken to walk along the path is noted. The amount of gas required to dose the area is evaluated (from knowledge of the building volume and the required initial concentration), and the gas flow rate needed to discharge that volume of gas in the time taken to walk along the path is calculated. The cylinder is set to discharge the gas at the required rate and the operator walks along the path carrying the discharging cylinder. Some mixing of air and tracer will occur as a consequence of the movement of the operator through the building.

Tracer density problem

If the tracer has a density which is different to that of air, that is if its molecular weight differs much from 29 g/mole, the concentrated tracer rises of falls (depending on its density) directly as it leaves the tube. Injection jets help to avoid this from happening but diffusers makes the phenomenon worse, since they lower the discharge speed of the concentrated tracer.

Since there is no nontoxic tracer gas having the density of air (appart ethane, which is explosive, the nearest are CO, HCN and NO!!), a simple approach is to dilute the tracer in compressed air and to use this diluted mixture. A 1% concentration is suggested. This achieves the correct molecular weight, increases the flow rate to aid mixing and makes the problem of flow control easier in relatively small rooms or for small concentrations.

Another possibility is to mix heavy tracers (such as SF_6 or Freons) with helium and light tracers (mostly He) with a heavier gas like CO_2 to adjust the average molecular weight to 29 g/mole. This mixture will follow the air movements immediately after injection.

Preparing such mixtures poses several problems. Compressed gaseous mixtures may be prepared in the bottle unless they are in liquid form when under pressure. These gases should be mixed with the carrier gas on injection by using mass flow controllers. Another possibility is to inject the desired quantity of tracer into an evacuated mixing box, and then to add the carrier gas prior to injecting the mixture into the room.

In any case, the tracer concentration should not exceed a value which significantly changes the density of air. A proposed limit is:

$$C_{lim} = 3\times10^{-4}\ \frac{\rho_{air}}{\rho_{tracer}} = 3\times10^{-4}\ \frac{29}{M_{tracer}} \qquad (5.5)$$

The factor 3.10^{-4} corresponds to a change in density for a temperature variation of 0,1 K in pure air. Such changes are very unlikely to have a significant effect on the air flows in a space. With usual tracers, this limit concentration is much higher that the concentration used.

Several experiments have shown that if the tracer is properly injected, the errors caused by the tracer density are negligible in relation to other sources of error *[Sandberg and Blomqvist, 1985]*.

5.3. Sampling Methods

5.3.1. Summary of Methods

Samples of air containing tracer gases need to be taken for analysis. There are several sampling methods, each one being adapted to a particular purpose.

Grab sampling using hand pumps and bags is very cheap, easy to install and needs few materials in the field. This method can be used for decay measurements in no more than a few zones, and for constant emission provided conditions remain constant.

The passive sampling technique, which relies on adsorbing the tracers on a porous material, is used to sample the air continuously in such a way that the amount of tracer collected is proportional to the dose. An advantage of the passive (and also of active adsorbing) sampling is that, because of the storage in the adsorbing material, very tiny concentrations can be detected. The passive samplers and emitters are the only testing material and can be sent for analysis by mail.

The above methods are most suitable for a small number of measurements.

For continuous monitoring of variable air flow rates in several zones over a long period of time, sampling networks using tubes and pumps are recommended. Such a sampling network is made of pipes returning from each zone to the analyzer, and one or more pumps to draw the air-tracer mixture through these pipes.

For such a purpose, the passive samplers can also be used in a programmable sampling unit composed of a pump and a multivalve connecting one sampler at a time to the measured zone. Multizone sampling is performed by using several such units, one in each zone.

5.3.2. Grab Sampling

This technique requires no expensive equipment to be used on the measurement site. The tracer gas is initially injected into the space and allowed to mix with the air. Because this whole process is designed to be as simple as possible, rudimentary injection techniques are usually employed: slowly releasing the tracer from a syringe, a plastic bag or a plastic bottle has shown itself to be adequate for the purpose.

An initial period of time is allowed to enable the tracer gas to reach a relatively uniform concentration throughout the building. The air in the space is then sampled. Air sampling can be performed using syringes, flexible bottles, air bags, or detector tubes (see § 5.4.6). The sample taken in this manner is intended to give an instantaneous picture of the tracer concentration at that time, hence the actual time taken to take the sample should be kept as short as possible.

After further defined periods of time, more samples can be taken. A minimum of two samples are required to evaluate the average air change rate between the sampling times, but often more are taken to ensure accuracy. The time interval between samples or the absolute time that samples were taken

must also be recorded.

Air samples are then returned to the laboratory for analysis. Concentrations are determined, the decay plotted and the air change rate evaluated. In the case of Dräger-type detector tubes, the gas concentration is determined directly by observation of the scale on the tube.

An advantage of grab sampling techniques is that non-technical personnel can perform the site tasks thus allowing laboratory trained staff to concentrate on the gas analysis procedures. Because it is kept at a central location, the analysis equipment is less likely to be damaged or to go out of calibration. As only simple site equipment is required, many buildings can be evaluated, often simultaneously, with little increase in costs. The main problem with this technique is that the results cannot be evaluated until some time after the site data is taken. Grab sampling may also be susceptible to unintentional errors by the non-technical site operators, or to the loss of samples in transit.

5.3.3. Passive Sampling

These sampling devices are metallic or glass tubes a few mm in diameter, partly filled with a given quantity of adsorbing material, such as activated charcoal. For transport and storage, these tubes are sealed with tight caps (e.g. polyurethane rubber caps). Properly used passive samplers adsorb all the tracers which are in the air entering the sampler (fig. 5.5). They are used to obtain a quantity of tracer which is nearly proportional to the dose (that is the time integral of the concentration) received during the measurement time.

Passive (or diffusive) sampling is initiated by opening one end of the tube for hours, days or weeks. Since the tracer reaching the adsorbent is adsorbed, there is a concentration gradient between the absorbent and the entrance of the tube. This leads to a diffusive flow of tracer, proportional to the concentration gradient.

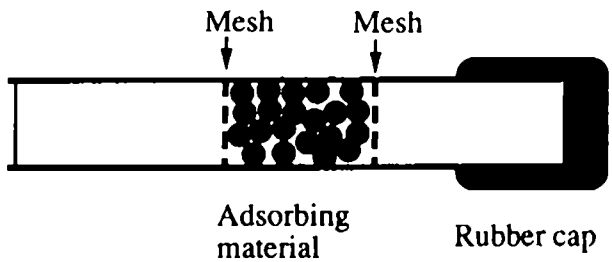


Figure 5.5: A passive sampler [Dietz, Goodrich, Cote, Wieser, 1984; Dietz, D'Ottavio, Goodrich, 1985].

Active sampling can be carried out with the same tubes by pumping the air through the tube. This technique is mainly used to achieve quick sampling. To ensure that all of the tracer contained in the air is trapped on the adsorbent, care must be taken not to sample too large a volume of air or not to pump the air through the adsorbent too fast, otherwise "break through" will occur.

A commonly used adsorbent is the "Ambersorb 347" by Rohm & Haas, Philadelphia, PA. *[Dietz, D'Ottavio, Goodrich, 1985].* "Poropak Q" from Pye Unicam is also used. The sampler shown in Figure 5.5 has a sampling rate of about 0,2 liters of air per day. This rate can be changed by changing the diameter of the tube or by changing the distance between the entrance and the adsorbent.

5.3.4. Networks, Pumps and Pipes

A star-type pipe network may be used in conjunction with valves and pumps to periodically collect samples of air in the monitored zones and to direct them to the analyzer, one after the other.

Any small, airtight air pump is suitable to pump the sampled air to the analyzer. Its model and size is chosen for a low working pressure, and with a flow large enough to flush the content of the pipe between two analyses. The working pressure is determined by the pressure drop through the sampling tubes and the analyzer, and is usually less than 1000 Pa.

The tubing must be airtight and should not significantly adsorb or absorb the tracer gases. For these reasons, polyvinyl chloride (PVC) pipes should be avoided, as well as Teflon if freons or PFT's are used. Suitable materials are nylon and polyethylene. Metallic pipes can also be used, but they are more difficult to install. **Never use tubes which have contained pure tracers** such as pipes which were used once for injection. Such pipes should be marked and used exclusively for injection.

The inner diameter of these tubes may range from a few millimeters to 1 cm. Smaller pipes lead to larger pressure drops and need stronger pumps, whereas larger pipes need larger flows to flush the content of the pipe in a reasonable time. To avoid large pressure drops and noise, the average speed in the tubes should not exceed 5 m/s.

The choice of tube size is influenced by the overall length of tubing required, i.e. by the size of the building. Some indications are given below.

The average air speed in a pipe of diameter D is given by:

$$v = \frac{4\,q}{\pi\,D^2} \tag{5.6}$$

Starting from a given air flow rate, q, it follows that the diameter D of the pipe should be large enough to avoid high speeds, larger that 5 m/s:

$$D > 0.5\sqrt{q} \tag{5.7}$$

In this case, the Reynolds number is smaller than 2 500, the flow is laminar and the pressure drop through one meter of such pipe is given by:

$$\frac{\Delta p}{L} = \frac{128}{\pi}\,\mu\,\frac{q}{D^4} \tag{5.8}$$

that is, for air with a viscosity $\mu = 18\hat{E}10^{-6}$ Pl

$$\frac{\Delta p}{L} = 733\times10^{-6}\,\frac{q}{D^4} \tag{5.9}$$

As an example, for an air flow rate of 100 l/h, that is 28×10^{-6} m^3/s , the minimum pipe inner diameter will be 2.6 mm to have an air speed of 5 m/s. In this case, the pressure drop will be 420 Pa/m, which may be too large in usual buildings. A pipe 4 mm inner diameter will have an air speed of 2.2 m/s and a pressure drop of 80 Pa/m, which allows for 12 m long pipes with a pump allowing 1000 Pa under-pressure at 100 l/h.

5.3.5. Injection and Sampling Ports Location

To ensure the best possible mixing of tracer with air in the measured zone, the tracer gases should be injected at the locations where natural convection or mechanical ventilation provides significant air currents. Examples are ventilation inlets and the bottom of heating devices.

Sampling locations should be kept away from injection points, but at locations which are representative of the air in the zone or where mixing can be reasonably assumed to be good. Ventilation exhaust grilles are generally good locations.

If there is a convective loop in the measured room, it is convenient to place injection and sampling points on this loop but at two opposite points. However, the points should not be placed near a door or a window which can be opened during the measurement.

In a two-storey building with an open staircase, the upstairs tracer injection points should be placed close to the staircase, while the sampling points should be near the outside walls.

To obtain a more representative sample, or to inject at several locations in a zone, the sampling or injection pipe may be connected to a mixing box or manifold, from which several pipes, of the same length and diameter, go to various locations in the zone.

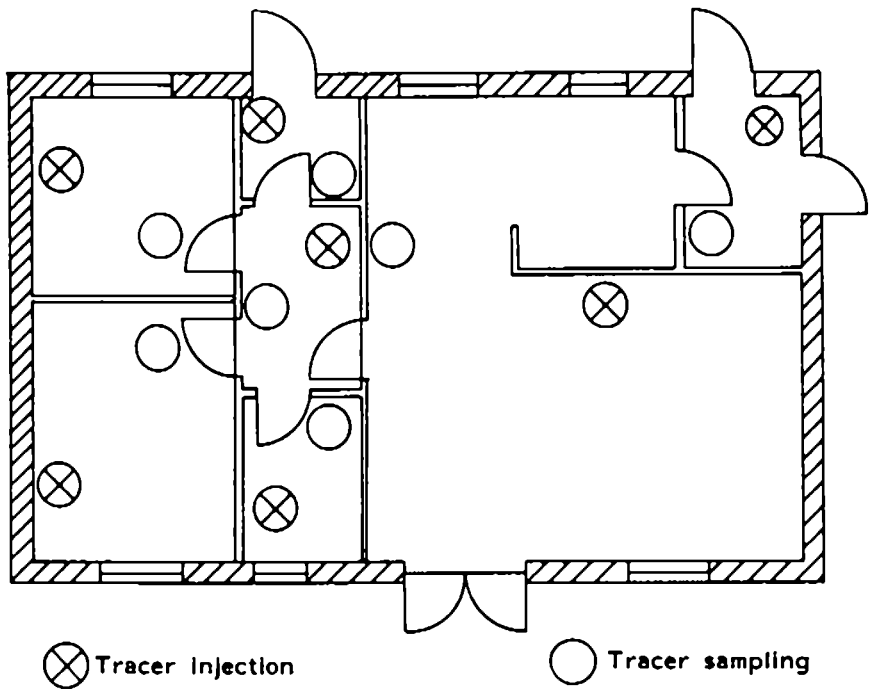


Figure 5.6: Example of injection and sampling locations in a flat. [Charlesworth, 1988]

The choice of PFT source types with zone location is important in multizone structures. Because of the stack effect in all houses, a source placed on the second floor will have a very low concentration in the basement. To improve the precision of its measurement in the basement, the second floor tracer selected should be one with the highest emission rate and the highest detectability, i.e., the earliest eluting tracer on the gas chromatographer column. Thus the choice for the second floor tracer in a 3-zone study is either PDCB or PMCP (see Table 5.13). The same reasoning extended to the other floors dictates that PMCH be used on the first floor and PDCH in the basement. The use of PDCB in one zone and PMCH in another zone in a 3-zone building should be avoided because those two tracers elute very close to each other and are therefore difficult to quantify without using special GC conditions. In stacked 4-zone structures, when both PDCB and PMCP must be used, the correct choice for the uppermost zone is PDCB, followed by PMCP in the next lower zone, PMCH in the next, and PDCH in the lowest zone.

Under no circumstances should the passive tracer sources and passive samplers be stored at the same location. The sources and samplers should definitely not be shipped in the same container and, ideally, not even shipped on the same day. For example, if transported in the same car or truck, there is a possibility of contamination. During field deployment, the samplers can be placed in the engine compartment of a vehicle (effectively outside) while the sources are maintained within the vehicle passenger compartment or truck. To this end it is usual for one or two passive samplers to remain as controls, that is, to remain unopened, for each series of home infiltration measurements.

One or two passive samplers are usually deployed in each zone of the home with the same location restrictions as the sources and at least 1 to 2 meters from any PFT source or source of air not representative of the room air (e.g., air from outside or another zone). Thus, the samplers are usually placed near another inside wall location (but at least 2 cm from any wall), and not in a flowing air stream without a shelter (such as an envelope or box). In the bedroom zone of a house, it is prudent to sample in the master bedroom plus one other bedroom; this provides a better average for that zone. The samplers are not temperature sensitive, but extremes should be avoided. They can be placed on a table or taped to the leg of a chair or table in any orientation.

5.3.6. Injection and Sampling Sequence

Multizone tracer gas active measurement methods generally use only one analyzer and often single bottles of each gas. This requires the zones to be scanned in sequence. There are several ways to plan these sequences, the two extremes being the following:

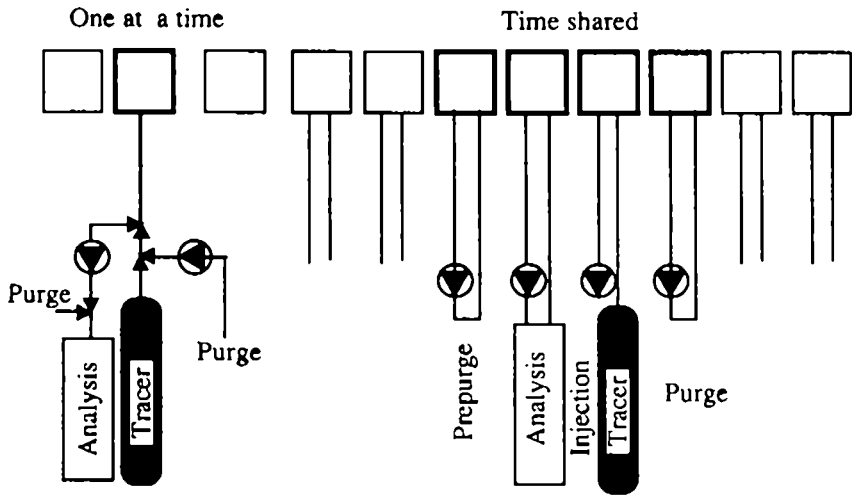


Figure 5.7: Two strategies for injection and sampling.

Sequential operation: The sample tube for a given zone is pre-purged with a fresh sample prior to analysis. In the constant concentration technique, the result of the analysis is used to calculate the appropriate amount of tracer to be injected. The injection pipe is subsequently purged and the cycle repeated on another zone.

Simultaneous operation: This applies mainly to the constant concentration method. The air from zone i is pre-pumped, while the air from the preceding zone, i-1, is analyzed. At the same time, the amount of tracer to be injected to zone i-2 (already analyzed) is calculated and delivered while the injection pipe of zone i-3 (already injected) is purged. This strategy is much more complex to control but is much faster.

Remember, however, that, in order to achieve good mixing, it is advantageous to inject the tracer continuously whenever possible. A series of short pulses spread evenly over time can simulate this continuous injection.

The air used to purge the pipes should ideally come from the measured zone and be returned to the same zone. However, if the flow rate in the sampling pipes is small, compared to the ventilation rate (which is the common case), it is reasonable to purge the injection tubes with outside air and to exhaust samples to the outside.

To ensure that the analyzed air has a concentration averaged over the time between two measurements, it is possible to continuously pump the air from each zone into an inflatable bag which is then periodically emptied into the analyzer *[Couston, 1989]*.

5.4. Analyzers

5.4.1. Objective of the Analysis

Measurement of the concentration of tracer in the air in each zone is the basic parameter needed for the interpretation and/or control of the concentration itself. There are several analyzing principles used in multitracer equipment. For any analyzer, the salient features to consider are the following:

Sensitivity: it is desirable to minimize the quantity of tracer gas used not only from the point of view of cost, but also toxicity, fire or other hazards which may be relevant. The more sensitive the analyzer, the lower is the required working concentration.

Selectivity: the analyzer should not be sensitive to other gases usually present in indoor air, e.g. nitrogen, oxygen, water vapor, carbon dioxide, argon, etc.

Speed: the time needed for the analysis must be considered, especially if several zones are to be sampled in sequence. This analysis time depends on the type of instrument and varies from

milliseconds for mass spectrometers up to several minutes for gas chromatographers or multitracer infrared analyzers. Faster analysis will enable more frequent sampling of each zone and hence provide more detailed data. Frequent sampling (e.g. every 5 to 10 minutes) is essential for the constant concentration technique to maintain accurate control of concentration.

Accuracy: the accuracy of the concentration measurement directly influences the accuracy of the results.

There are several principles employed for analysis for tracer gas concentrations, which differ in the gases analyzed, the range of concentration detected, accuracy, speed, ease of use and cost. These principles are discussed and specific examples are given.

5.4.2. Infrared Absorption Spectrometry

Any polyatomic gas molecule exhibits vibration modes which are excited by infrared radiation. This absorption of radiation by tracer gas molecules is used as a measure of the number of, or concentration of tracer gas molecules in the path between an infrared source and detector. This technique is referred to as "infrared absorption spectroscopy".

Infrared absorption spectrometers may be either dispersive or non dispersive types, and both are in common use. Dispersive spectrometers are tuned by the operator to a fine band of frequencies specific to the gas of interest and the absorption is measured by any convenient infrared detector.

In non-dispersive devices, on the other hand, all the infrared radiation contained in the absorption bands of the tracer is used (fig. 5.8). The infrared light beam is sent through both a reference channel containing N_2 or pure air and an analysis channel which contains a sample of room air. A chopper is then used to alternately pass the radiation from each channel to an analysis chamber containing a pure sample of the tracer gas. This gas heats and cools in response to the modulated beam. The heated gas expands through a measuring channel into an expansion chamber. The resulting alternating flow through the measuring channel is measured by a highly sensitive gas flow detector which transmits an electric signal.

Analyzable tracers: N_2O, SF_6, CF_3Br (Halon 1301). Other detectable gases, such as H_2O, CO_2, benzene, alkanes, etc., are not suitable as tracers.

Sensitivity: 200 parts per million at full scale deviation (ppm fsd) for N_2O, 20 ppm fsd for SF_6 and CF_3Br.

Interfering gases: care must be taken to eliminate the effects of other gases absorbing at similar frequencies (cross sensitivity), particularly water vapor and CO_2 present at high concentrations in the air. Filters are used to minimize the effect but humidity must be measured to make the final correction.

Analysis time: 10 to 50 s

Accuracy: ±1% of fsd if the zero drift is controlled

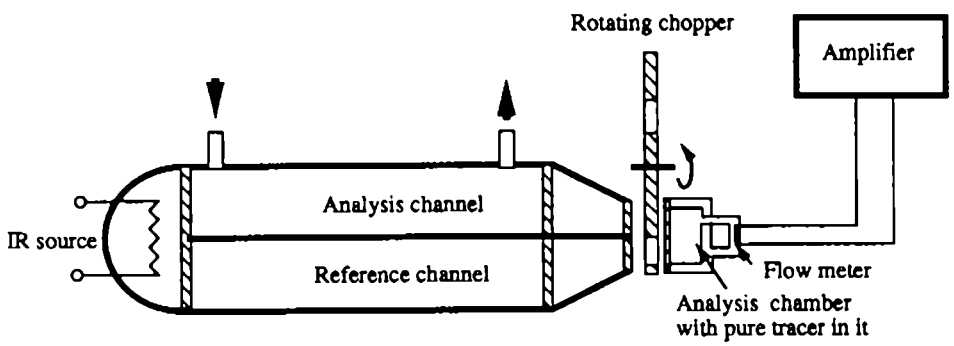


Figure 5.8: Principle of a non-dispersive analyzer. [from Leybold Heraeus Company, 1986]

5.4.3. Photoacoustic Detector

This analyzer is also an infrared absorption spectrometer, but uses a different detector. An infrared radiation beam is first chopped then optically filtered to leave only frequencies which are absorbed by the tracer of interest. This beam then enters a gas-tight chamber containing the air sample. As above, the sample is heated and cooled in phase with the chopping frequency, creating sound waves in the chamber. These sound waves are detected by microphones, hence the "photoacoustic" effect.

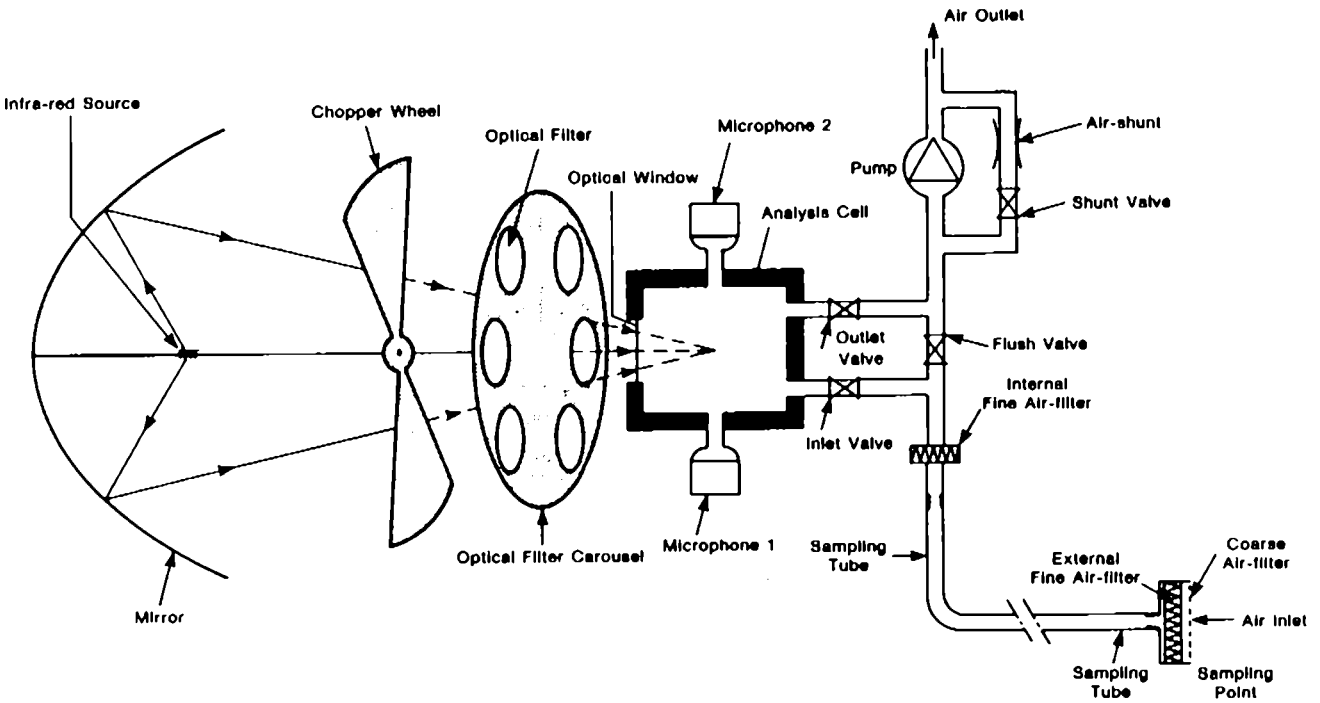


Figure 5.9: Principle of the photoacoustic analyzer [Brüel & Kjaer Company, 1989]

Analyzable tracers: N_2O, SF_6, Freons F11, F112, 113 and 114, Halons (one filter for each tracer). Other detectable gases are not suitable as tracers, such as H_2O, CO_2, benzene, alkanes, etc.

Sensitivity: the detection limit depends on the tracer but is typically 0.05 ppm, and the dynamic range is 10^3. The lowest full scale range may then be 2 ppm but 10 ppm fsd is recommended with usual tracers. The sensitivity for N_2O, CO and CO_2 drops strongly when these gases are diluted in dry nitrogen, as is often the case for calibration gases. Adding a special "Nafion" tube in the sampling circuit allows the moistening of the mixture in order to recover the normal high sensitivity.

Interfering gases: Several gases (which are not necessarily present in the air) may interfere with each tracer. Therefore, filters and tracers should be chosen in accordance with manufacturers specifications.

Analysis time: 30 s for one gas, 105 s for 5 gases and H_2O.

Accuracy: ±1% of fsd.

5.4.4. Mass Spectrometry

The pressure of the room air sample is first lowered to about 10^{-5} Pa by pumping it through a capillary tube. The molecules of the sample are then ionized and passed into a mass spectrometer. The most suitable spectrometer is the quadrupole mass spectrometer, which is currently used in vacuum processes to analyze the residual gases (RGA or residual gas analyzer).

The gases entering into the analyzer are ionized and the positive ions are separated by directing them axially between two pairs of rods creating an electric field at variable radio frequency. The ions follow a helicoidal path. Only ions having a charge-to-mass ratio which corresponds to a given radio frequency reach an orifice at the end of that path and pass into an electron multiplier, whose signal is proportional to the number of incoming ions.

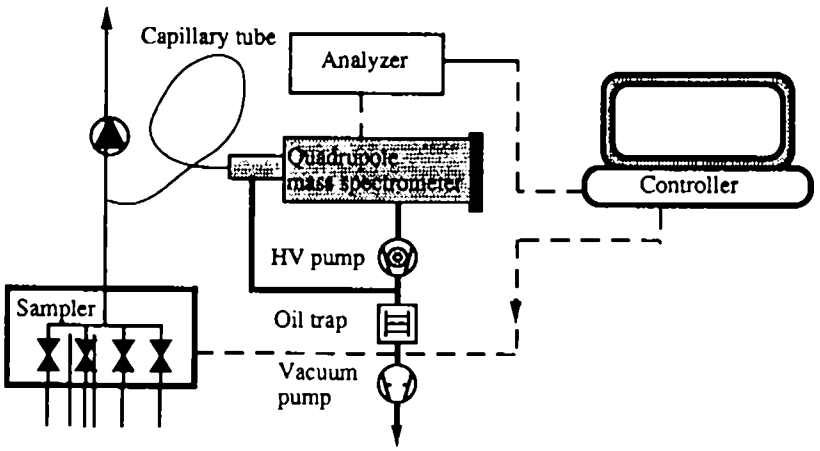


Figure 5.9: Principle of the mass spectrometer used for tracer gas analysis [from Sherman and Dickerhoff, 1989].

Gas	Ions	Mass*	Comments
SF_6	SF_5^+ SF^+	127 51	7.6% of mass 127 peak. Interferes with Freon 22
Freon R22	CHF^+ $CHClF^+$ $CHCl_2^+$	51 69 85	Interferes with SF_6 2.1% of peak 51. Interferes with R14 and R13B1 1.5% of peak at mass 51. Interferes with R12
Freon R12 Freon R13B1 Freon R12B2+	$CClF_2^+$ CF_3^+ CF_2Br^+	85 69 120	Not commonly available
n-Butane	$C_4H_{10}^+$ $C_3H_7^+$	58 43	Flammable above 2% concentration
He Ne	He^+ Ne^+	4 20	5,24 ppm background concentration Expensive, 18 10^{-12} background concentration
Ar	*Ar^+*	*40*	*Background of 1%. Not a tracer but a good reference.*

Table 5.10: Most used tracers in mass spectrometer technique [Sherman and Dickerhoff, 1989].
**: Mass-to-charge ratio of the most common isotopes, singly charged.*

Such instruments deliver a signal for each molecule having a given charge/mass ratio. A given molecule may give several signals at different radio frequencies, since ionization may often break the molecule. For example, water vapor gives a peak not only at mass 18 (H_2O+), but also at mass 17 (HO+), 16 (O+), 2 (H_2+) and 1(H+). The electric current is proportional to the concentration, but the sensitivity depends on the analyzed gas.

Analyzable tracers: any tracer which can be distinguished from the normal components of air. Confusion may occur if the molecule or a part of it has the same charge/mass ratio as components of air. Examples are shown in table 5.10.

Sensitivity: 2 10^{-6} for tracers with low background concentration.

Interfering gases: any gas present in the sample may interfere with another, but it is nevertheless possible to analyze up to 7 tracers without there being too much interference from the gases in the air or between the tracers themselves.

Analysis time: a few milliseconds

Accuracy: 1%

5.4.5. Gas Chromatography

A pulse of the sampled air is injected into a separating (chromatographic) column, a tube in which adsorbent material is packed. This column is heated and the pulse of sample is pushed with a flow of inert carrier gas. The various components of the sample pass through the column at various speeds according to their affinity for the adsorbent material. At the end of the column, the components emerge in sequence and can be quantitatively detected with a suitable detector. Both flame ionization (FID) and electron capture detector (ECD) have been used.

In the flame ionization detector, the ions produced when organic compounds are burned into an air-H_2 flame are collected by a pair of polarized electrodes and the current produced is amplified before measurement (figure 5.10). This detector is rugged, reliable, easy to maintain and operate, and is by far the most used in gas chromatography, since it combines a good sensitivity to organic compounds, (limit of detection of about 10^{-9} g) with a good linearity (up to 10^7).

However, organic compounds are not very good tracer gases and the electron capture detector, which is much more sensitive to halogenated compounds is the most common in tracer gas analysis. In this detector, a radioactive nickel cathode emits electrons, which are received on an anode. Halogens capture these electrons, lowering the received current and thereby indicating the tracer concentrations. ECD is popular since it can measure fluorinated tracers to exceptionally low concentrations, therefore, very little gas is needed.

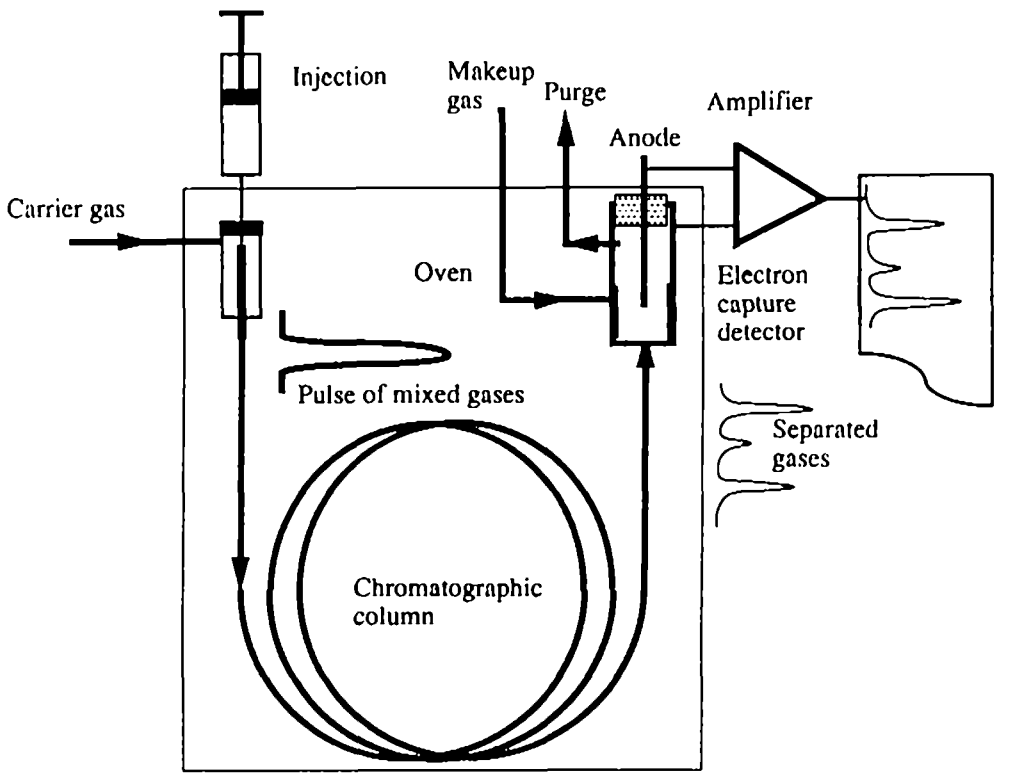


Figure 5.11: Principle of the gas chromatography, shown with an electron capture detector.

Analyzable tracers (with ECD: any halogenated compound like SF_6, Freons, PFTs (perfluorocarbons or perfluorocycloalkanes)

Sensitivity: from ppb (10^{-9}) range for SF_6 down to 10^{-14} for the PFTs.

Interfering gases: H_2O, O_2 (oxygen traps and desiccators are used to suppress these effects).

Analysis time: a few minutes but can be lowered down to 20 seconds by shortening and backflushing the column, if high selectivity is not needed.

Accuracy: Depends on the quality of the calibration, but can be ±2% of reading.

5.4.6. Chemical Indicator Tubes

This is a single shot method to estimate the air change in a single zone by the decay or constant injection technique with CO_2 as tracer.

CO_2 concentrations are obtained using the detector tubes. These are glass tubes packed with a selective solid absorbent which gives a color reaction with carbon dioxide. The tubes used are sensitive to carbon dioxide in the 0.01-0.30% range. Tubes as supplied by the manufacturer are sealed at both ends. To make a measurement the seals are broken, one end of the tube (the correct end is indicated on the tube), is inserted into a pair of specially designed hand bellows, the other end being left open to sample the air tracer mixture. Figure 5.12 shows a tube and bellows being used to make a measurement.

Figure 5.12: Chemical tube and sample pump (Dräger)

By making the prescribed number of strokes of the hand held bellows, the correct amount of air is drawn through the tube. This enables the carbon dioxide evaluation to be made. The glass tube has graduation marks on it, and the length of the discoloration caused by the reaction indicates the concentration of carbon dioxide in the room air. Detector tubes can only be used once and must be discarded after each sample taken.

This single shot method is not very accurate but it is cheap and easy to operate. Therefore, it is suitable for a rough, first estimate of the air change rate. The interpretation of the result is performed using the integral decay method (see § 4.2.3).

Analyzable tracers: CO_2, H_2O (and many toxic gases which are not useable as tracers.)

Sensitivity: 0.01 to 0.3 % range for CO_2

Analysis time: a minute

Accuracy: ± 5 or 10% of full scale

5.4.7. Calibration of the Analyzers

Any analyzer should be periodically calibrated by analyzing standard samples, which are mixtures of the tracers in air or other (inert) gas. The calibration mixtures containing N_2O and CO_2 must be moistened when a photoacoustic detector is used.

To transfer the calibration mixture from the containers to the analyzer, never use relief valves or pipes which were previously used with pure or high concentration tracers.

During the measurements, it is recommended to periodically sample and analyze the outside air as a convenient zero reference, even if no tracer is expected in the outdoor air.

5.5. Control systems

5.5.1. Features of the Control System

Any measurement must be carefully controlled to get the appropriate results. In tracer gas measurement methods, the amount of injected tracer, its mixing in the air of the measured zone, the analysis of the tracer gas concentration and the timing are the fundamental control parameters.

Measurement using the simplest methods are directly operator-controlled, but the control a multitracer or a constant concentration instrument by hand is a tedious task, which becomes impossible for long term monitoring. Therefore, it is useful to employ an automated control system to perform these tasks as follows:

- control the injection and sampling sequence,
- calculate, if necessary, the correct amount of tracer to be injected in each zone,
- monitor the analyzer(s),
- record the results of the measurements, which may include the amount for the tracer injected in each zone, the tracer concentrations of each tracer in each zone and the temperatures in each zone,
- optionally, the control system may be used to interpret the measurements on line and give the results immediately.

5.5.2. Algorithms to Control Constant Concentration System

A constant concentration tracer gas (CCTG) measuring system needs a control algorithm to calculate, at each sampling time, the required tracer gas injection rate to keep the gas concentration at a target level.

In an inhabited multizone building, the control algorithm has to respond quickly to large variations of interzonal airflows and/or outside air infiltration. A few authors *[Bohac, Harrje, 1985; Bohac, 1986; Sandberg, Blomqvist , 1985]* have described in detail the implemented algorithm of their CCTG systems. Most systems use common control methods such as a proportional (P), a proportional-integral (PI) or a proportional-integral-differential (PID) control algorithm. A very efficient control algorithm *[Compagnon, Kohler, Roecker, Roulet, 1988]* is presented in appendix 6.

5.6. Tracer gases

5.6.1. Ideal Properties

The tracers used for multizone air flow measurements should ideally have the following properties:

1 neither flammable nor explosive, for safety reasons,
2 non toxic, for health reasons and measurements in inhabited buildings,
3 density close to the air density (i.e. a molecular weight close to 29) or diluted in air to ensure easy mixing,
4 the tracer should not be absorbed by furnishings, or decompose, or react with air or building components,
5 easily detectable, preferably at low concentrations,
6 low background concentration in the outside air,
7 natural sources within the test space should have a flow much lower than the flow of the source used for measurement,and
8 the tracer should be cheap in the quantity required for measurement.

Item 3 is important mainly if the concentration is relatively high (e.g. 10 ppm or higher). For this reasons and to achieve also items 1, 2 and 8, the items 5 through 7 are essential.

5.6.2. Effective Properties

Table 5.13 shows properties of tracers which have been used and appropriate detection methods. Note that the mass spectrometer (MS) can potentially analyze any tracer. Table 5.14 shows their background concentrations.

It can be seen from table 5.15, that no tracer satisfies all the requirements. Moreover, because of possible interferences in the analyzer of multitracer instruments, the use of one tracer may forbid the choice of several interesting other tracers.

Tracer name	Chemical formula	Molecular weight	Density /air @NTP	MAC* [ppm]	MDC# [-]	Analyzer (besides MS)
Helium	He	4	0.14	-	$>6\times10^{-6}$	
Neon	Ne	20	0.69	-	$>20\times10^{-12}$	
Carbon dioxide	CO_2	44	1.53	5000	3×10^{-6}	IR
Nitrous oxide	N_2O	44	1.53	25	50×10^{-9}	IR
Sulfur hexafluoride	SF_6	146	5.10	1000	0.1×10^{-12}	ECD (IR)
Freon R11	$CFCl_3$	137.4	4.74	1000	1×10^{-12}	ECD (IR)
Freon R12	CF_2Cl_2	120.9	4.17	1000	50×10^{-9}	ECD (IR)
Freon R13	CF_3Cl	104.5	3.60	1000	50×10^{-9}	ECD (IR)
Freon R22	CHF_2Cl	86.48	2.99	1000	20×10^{-9}	ECD (IR)
Freon R111	CCl_3-CCl_2F	220.3	7.60	1000		ECD (IR)
Freon R112	CCl_2F-CCl_2F	203.9	7.03	1000	50×10^{-9}	ECD (IR)
Freon R113	CCl_2F-$CClF_2$	187.4	5.90	1000	50×10^{-9}	ECD (IR)
Freon R114	$CClF_2CClF_2$	170.9	5.90	1000	50×10^{-9}	ECD (IR)
Freon R115	$CClF_2CF_3$	154.4	5.31	1000		ECD (IR)
Halon BCF or Halon 1211	CF_2BrCl	165.4	5.53	?	0.5×10^{-9}	ECD (IR)
Halon R13B1 or Halon 1301	CF_3Br	148.9	4.99	?	10×10^{-12}	ECD (IR)
Perfreons			Liquid @NTP			
PB or Perfreobenzene	C_6F_6	186	(6.4)		ECD	
PMB or Perfluoromethylbenzene	$CF_3C_6F_5$	236	(8.1)		ECD	
PMCH or Perfluoro-methyl-cyclohexane	$CF_3C_6F_{11}$	350	(12.1)	-	10^{-14}	ECD
PDCH or Perfluoro-dimethyl-cyclohexane	$CF_3CF_3C_6F_{10}$	400	(13.8)	-	10^{-14}	ECD
PMCP or Perfluoro-methyl-cyclopentane	$CF_3C_5F_9$	300	(10.3)	-	10^{-14}	ECD
PDCB or Perfluoro-dimethyl-cyclobutane	$CF_3CF_3C_4F_6$	300	(10.3)	-	10^{-14}	ECD

*: MAC = Maximum Acceptable Concentration for health safety
#: MDC = Minimum Detectable Concentration using the best available analyzer in 1989. The useful concentration should be at least 100 times higher.
IR: Infrared absorption spectrography or photoacoustic detector
ECD: Gas chromatography and electron capture detector.

***Table 5.13:** Properties of the most frequent gases used as tracers.*

A comparative experiment of the mixing of three different tracers (SF_6, N_2O and He) was performed to study the effect of the density *[Niemelä, Lefevre, Muller, Aubertin, 1990]*. This study showed that differences may occur when the tracer are not well mixed with air at the injection location or before. The authors propose various efficient mixing injectors for that purpose.

However, the differences observed were only slightly greater than other experimental errors, and density effect is not a major cause of error for tracer gas measurements.

It is finally remembered that non toxic tracer gases of various densities may be useful to simulate the behavior of contaminants of similar densities.

Gas	Formula	Rural concentration	
Nitrogen	N_2	780,9	10^{-3}
Oxygen	O_2	209,5	10^{-3}
Water vapor	H_2O	20	10^{-3}
Argon	Ar	9,3	10^{-3}
Carbon dioxide	CO_2	335	10^{-6}
Helium	He	5,24	10^{-6}
Methane	CH_4	1,48	10^{-6}
Nitrous oxide	N_2O	315	10^{-9}
Ozone	O_3	35	10^{-9}
Nitrogen oxides	NO_x	3	10^{-9}
Methyl chloride	CH_3Cl	630	10^{-12}
Freon R12	CCl_2F_2	305	10^{-12}
Freon R11	CCl_3F	186	10^{-12}
Carbon tetrachloride	CCl_4	135	10^{-12}
Chloroform	$CHCl_3$	20	10^{-12}
Neon	Ne	18	10^{-12}
Sulfur hexafluoride	SF_6	850	10^{-15}
Halon 1301	CF_3Br	750	10^{-15}
PDCH or Perfluoro-dimethyl-cyclohexane	$CF_3CF_3C_6F_{10}$	22	10^{-15}
PMCH or Perfluoro-methyl-cyclohexane	$CF_3C_6F_{11}$	4,5	10^{-15}
PMCP or Perfluoro-methyl-cyclopentane	$CF_3C_5F_9$	3,2	10^{-15}
PDCB or Perfluoro-dimethyl-cyclobutane	$CF_3CF_3C_4F_6$	0,34	10^{-15}

Table 5.14: Background concentration of some gases (from [Dietz, D'Ottavio, Goodrich, 1985]).

Name	Compliance with the quality							
	1	2	3	4	5	6	7	8
Helium	++	++	--	++	+	-	+	+
Neon	++	++	++	++	++	+	++	--
Carbon dioxide	++	-	+	-	++	--	--	+++
Nitrous oxide	*	-	+	-	+	+	+	++
Sulfur hexafluoride	#	+	-	+	++	++	++	+
Freon R11, R12, R13	#	+	-	+	+	+	+	+
Freon R111 to R115	#	+	--	+	+	+	+	+
Halon BCF	#	+	--	++	+	++	+	-
Halon R13B1	#	+	--	++	+	++	+	+
Perfreons (PFT)	++	++	--	++	+	++	++	+++

++ Very good for that property + good - not so good -- very bad
* Is not combustible but a good oxidant at high concentration and temperature.
\# Is not combustible but decomposes in a flame, producing toxic chemicals

Table 5.15: Qualities of some tracers

1 Non flammable nor explosive
2 Non toxic.
3 Density close to the air density.
4 Neither absorbs nor reacts.
5 Easy to analyze.
6 Low background concentration.
7 No sources in the measured enclosure.
8 Cheap to use.

6. Examples of Systems

6.1. Introduction

This Chapter describes several measurement techniques in detail and gives examples of instruments and apparatuses. For each technique, the description is generally divided into the following sections:

- **introduction**, which contains a brief presentation of the system,
- **principle of operation**,
- **material and software**, providing full details of the necessary equipment and software needed, and
- **procedure of operation**.

Most of the instruments were described by the researchers which have developed them or use them currently. Their names and affiliations are listed below together with the presented techniques, distributed in four groups:

Single Tracer, Variable Concentration Instruments.

Tracer Gas Decay, Site Analysis

Tracer Gas Decay Rate - Grab Sampling in Bags or Bottles.

Tracer Gas Decay Rate - Grab Sampling in Detector Tubes.
Mats Sandberg, NSIB, Box 785, S-801 29 Gävle, Sweden.

Integral Pulse Injection Tracer Technique
J. Axley, A. Persily, N I S T, Gaithersburg MD (USA)

Single Tracer, CCTG Instruments

The Princeton CEES Constant Concentration Tracer Gas
David Harrje, Center for Energy and Environmental Studies, Princeton University (USA)

EMMARA: The Automatic CCTG Instrument of the LNE
P. Launey, Laboratoire National d'Essais, 5, Av. E. Fermi, F-78190 Trappes, France.

NIST Automated Air Infiltration and Ventilation Measurement System
R. Grot, National Institute of Standards and Technology, Gaithersburg MD, (USA)

Multi Tracer, Pulse or Decay Instruments.

BRE Multi-tracer Multizone Air Exchange Rate Measurement Systems
Richard Walker, Building Research Establishment, Garston Watford WD2 7JR, UK

Parallel Column System (PCS) for the Measurement of Air Flows Between up to Three Zones
Parallel Detector System (PDS) for Measurement of Air Flows Between Four or More Zones
Roger Edwards University of Manchester Institute of Science and Technology, Manchester M6O 1QD, UK, and Chris Irwin (Willan Building Services)

Multi-tracer Instrument from Brüel & Kjaer
Bjorn Kvisgaard, Brüel & Kjaer, Naerum, DK.
A Multi-tracer system with variable internal sampling.
S.B. Riffat, Department of Civil Engineering, Loughborough University of Technology, Loughborough, Leicestershire, LE11 3TU, (UK)

Multi Tracer, CCTG or CITG Instruments.

MTMS: The LBL Multigas Tracer Measurement System
Max Sherman, Energy Performance of Buildings Group, L. B. L., Berkeley, Cal (USA)

CESAR: Compact Equipment for Survey of Air Renewal
R. Compagnon, C. Roecker and C.-A. Roulet, Laboratoire d'Energie Solaire et de Physique du Bâtiment, Ecole Polytechnique Fédérale, LESO-EPFL, CH-1015 Lausanne

MATE: Multipurpose Automated Tracer Gas Equipment
Peter Wouters, Luk Vandaele, R. Bossicard, Belgian Building Research Intitute (WTCB/CSTC), Aarlenstraat 53/10, B-1040 Brussels

Perfluorocarbon tracer (PFT) Measurement Technique
David Harrje, Center for Energy and Environmental Studies, Princeton University (USA)
Russell Dietz, Brookhaven National Laboratory (USA)

The SIB passive tracer gas method
Hans Stymne, SIB, P.O. Box 785 S-80129, Gävle Sweden

The Automated Apparatus of the Politecnico di Torino
R. Borchiellini and M. Calì, Dipartimento di Energetica, Politecnico di Torino, Italy

6.2. Single Tracer, Variable Concentration Instruments.

6.2.1. Tracer Gas Decay, Site Analysis

Introduction

This technique was one of the first to be used to estimate the air change rate in a zone of a building *[Lagus, 1980]*. A single quantity of tracer gas is released and mixed with the air within a building. The change in tracer concentration with time is monitored. The tracer is removed from the building by the ventilation air and, ideally, the concentration will show a negative exponential decay. By examining this decay the air change rate of the building can be evaluated. Chapter 4 of Part III presents a full treatment of the mathematics required to perform this evaluation.

This method is suited to situations where a rapid measurement of the air change rate is needed. Although automated decay systems have been produced (see, for example, *[Hartmann and Muhlebach, 1980]*) this reduces the simplicity of use which makes this technique attractive to non-specialist consultants and engineers. The setting up procedure is relatively simple and a minimum of equipment is required. However the limitations concomitant with the simplicity of this technique must be noted. By only measuring the tracer concentration at a single point, it is assumed that the evaluated air change rate at this point is representative of the space as a whole. This may only be true in the case of small spaces, and where the air and tracer are well mixed (see Section 5.2.4 for a discussion on mixing). Therefore inferences about the ventilation behavior of the building as a whole, especially large multizone buildings, must be treated with caution.

Equipment and Instrumentation

This basic technique relies upon only a single tracer gas and a suitable analyzer. Several combinations of tracer and analyzer can be used. One combination will be described here, but the use of other tracers and analyzers should not be precluded.

A much used and well documented combination for this type of measurement is sulphur hexafluoride tracer gas used with a gas chromatographer electron capture detector. An account of the properties of tracer gases is given in Section 5.6, and a description of this gas analysis method is provided in Section 5.4.

Procedure

The building should first be prepared so as to correspond to the desired measurement situation. A small amount of sulphur hexafluoride is released into the test space. The volume of tracer required will depend upon the detection range of the gas analyzer and on the volume of the building. A suitable initial concentration for an electron capture detector is 5-15 ppb, this is 5-15 ml of pure SF_6 per 1000 m^3 of building volume. The tracer is then mixed to the ambient air (see Section 5.2).

The aim of the sampling process is to obtain values of the tracer gas concentration at several known time points after the gas is released. Air samples are pumped through a pipe, the end of which being located at the place to be measured. A valve and a sampling loop is used to inject a precise volume of room air into the gas chromatographer (figure 6.1).

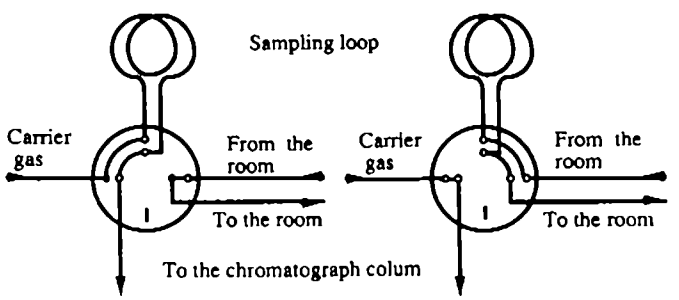


Figure 6.1: Use of a 6-port valve with a sampling loop to send known volumes of air to the GC column.

The sample valve is turned and held open for two seconds and then closed. This sends an air sample down the chromatographer column towards the detector. About five seconds later a large peak will show on the meter and chart. This is caused by oxygen in the air sample reaching the detector. Oxygen

is an electron capturing gas. After about 20-30 seconds the sulphur hexafluoride peak appears. The concentration of tracer can be evaluated from either the height of the peak or the area under the peak. The sample valve is then operated at regular timed intervals (1-2 minutes) until sufficient data points are obtained. The concentration decay rate, hence the air change rate, is deduced from the records of the values of the concentrations at the various times.

6.2.2. Tracer Gas Decay Rate - Grab Sampling in Bags or Bottles.

Introduction

This technique has been in use since 1980 *[Grot, 1980]* to estimate the air change rate of dwellings or larger buildings over a 2-3 hour period by the decay rate of a tracer gas. On site gas injection and sampling is performed using flexible plastic bottles, syringes or plastic bags. Air samples obtained in this manner are returned to a central laboratory. They are analyzed for tracer gas concentration from which the air change rate is evaluated using the decay data.

Equipment and Instrumentation

The equipment can be divided into two categories:

Field Equipment: The tracer gas (sulphur hexafluoride is in common use for this technique and will be discussed here) is injected and sampled using flexible polyethylene bottles (e.g. 500 ml), syringes or plastic bags. Several receptacles are required to make a test, e.g. for a dwelling - one for injection and five for sampling. In order to avoid cross-contamination, the injection container must be clearly marked and never used for sampling. Each sampling receptacle must also be marked to enable it to be uniquely identified. A simple numbering system is adequate. It may be necessary to aid tracer gas mixing using paddles or small electric fans.

Laboratory Equipment: The laboratory instrumentation essentially consists of a gas analyzer. In this case a specific analyzer i.e. a chromatographer with electron capture detector will be discussed. This commercially available unit is specially adapted to enable samples to be analyzed for sulphur hexafluoride concentration. The chromatographer sample line is fitted with a small hypodermic needle. This is inserted into the rubber gasket closing the sample container which acts as a septum. Air is withdrawn at a controlled rate measured by a sensitive flow meter and needle valve. Pressure is exerted on the container to avoid the entry of room air. This is achieved by using a weighted clamp which presses down on the container under examination.

Procedure

A clearly marked container is charged with tracer in the laboratory. This is taken, along with five sample receptacles, to the measurement location. The tracer is then released into the building. This is easily performed by loosening the cap and walking around the building while gently squeezing the container.

Air and tracer should then be allowed to mix. After the initial mixing period (approximately half an hour), the first sample receptacle can be filled with air from the measurement site. The receptacle is squeezed and released, rotated 90 degrees and the procedure repeated for a total of 10 cycles. This should adequately fill the receptacle with air from the given location. The cap should then be firmly replaced on the receptacle. From then on, further samples can be taken at given time intervals. A sample interval of half an hour is often used.

The receptacles should be clearly numbered and the time and location of samples must be recorded. A simple logging sheet is useful for this purpose. Wind, temperature and other relevant data can also be recorded on this sheet.

Synchronous samples may be taken at several locations in the same building. This could be used, for example, to examine air change rates for individual floors of a multistory building. If sufficient personnel are available, simultaneous sampling can be performed in many buildings in the same area. This would allow the air change rates of those buildings under similar weather conditions to be compared.

Samples are then returned to the laboratory for analysis. Several individual measurements of concentration may be obtained from each container and a mean value obtained. Because the receptacles are fitted with the rubber septum, they can be reused many times, providing the air from the previous sample is fully discharged.

If tracer injection and sampling takes place simultaneously at several measurement sites in the same

general area, the inter-comparison of many buildings under the same weather conditions can be performed. This is illustrated in Figure 6.2. Here simultaneous air change measurements were made in 15 nominally identical houses and the houses are arranged from left to right in increasing air change rate order.

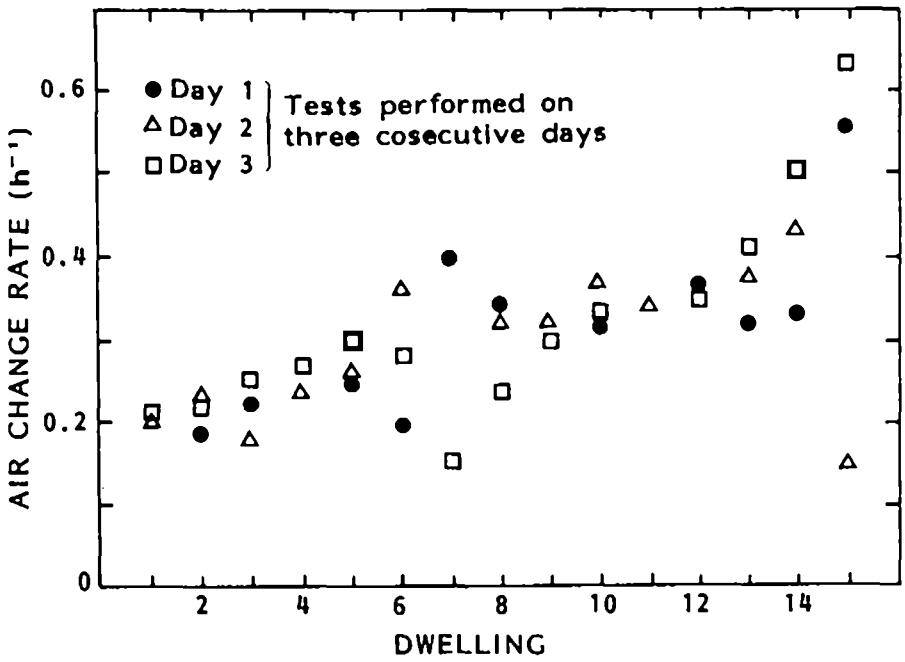


Figure 6.2: Simultaneous measurements of 15 dwellings [Harrje, Gadsby, and Linteris, 1982]

6.2.3. Tracer Gas Decay Rate - Grab Sampling in Detector Tubes.

Introduction

This technique enables the total building air flow rate to be evaluated. It has been tested in a mechanically ventilated controlled flow rate test house, with a maximum of two occupants [*Sandberg and Sandberg, 1987*]. Site work had also been performed in dwellings with mechanical extract ventilation.

Principles of operation

Carbon dioxide is used as a tracer gas and its variation in concentration with time is monitored on site using detector tubes (see § 5.4.6). In occupied spaces a simple exponential decay of the tracer does not occur, this is due to the carbon dioxide exhaled by the occupants. Hence it is not possible to use the standard decay curve method, to evaluate the air change rate. Instead a slightly more complex analysis must be utilized, which is presented in Section 4.2.

Materials and Instruments

Two essential items are required for this technique. These are a source of carbon dioxide and a set of detector tubes with bellows. The carbon dioxide source must be capable of producing an initial concentration of tracer in the test building of approximately 2000 ppm (0.2% by volume). This is easily achieved by releasing a short burst of carbon dioxide from a gas cylinder. Mixing fans may be used in order to obtain a uniform concentration of carbon dioxide throughout the test space.

Tracer concentrations are obtained using the detector tubes described in Section 5.4.6..

Procedure

Before the measurement commences, the volume of the building and the occupancy level must be noted. Both of these parameters are required in order to be able to calculate the air change rate. The tracer gas is then released and small mixing fans can be used to maintain a constant spatial concentration. An ideal starting concentration is in the region of 2000 ppm.

After release, the tracer concentration should be monitored at several evenly spaced time points. A total of five points at 15 minute intervals has been found to be adequate for this purpose.

An individual measurement may take some time to perform. Typically ten strokes of the hand held bellows are required to draw sufficient air through the tube. Each stroke may take in the region of 15-25 seconds to perform. Hence the "spot" measurement of concentration is actually obtained over a period of a few minutes. This, however, should not create difficulties providing consistent measurement and time logging procedures are adopted.

Gas detector tubes are available from:

Drägerwerk AG, Lübeck
Federal Republic of Germany
Tel: Int +49 451 882-0
Telex: 26807-0

This company name has become synonymous with this type of detector tube. Although based in Germany the company has suppliers world wide.

6.2.4. Integral Pulse Injection Tracer Technique

Introduction

The integral pulse injection tracer gas technique combines pulse injections of tracer gas with integral mass balance analysis of the tracer gas concentration response to determine air flow rates between the zones of multi-zone air flow systems *[Axley, and Persily, 1988; Persily and Axley, 1990]*. For building air flow systems, or portions of them, the air flow system is first idealized by an appropriate multizone model of well-mixed zones. Pulse injections of tracer gas are then applied to each zone independently, and the concentration response of each zone is measured. From the concentration response data, the multizone integral mass balance equations are formed and solved to determine the air flow rates between the zones. As in any multizone tracer gas technique, the air flow rates that are determined and the accuracy of these determinations are dependent not only upon the air exchange characteristics of the building, but also on the appropriateness of the system idealization employed.

Measuring Technique

While the integral pulse injection tracer technique is generally a multi-zone measurement approach, it can also be applied to determine the airflow rate through a duct and the air exchange rate associated with a single zone. In the duct pulse application, one injects a known volume of tracer gas into the air stream flowing within the duct. The tracer gas concentration response downstream from the injection is then measured, starting before the injection and continuing until after the tracer gas concentration has decreased to the pre-injection concentration.

An integral formulation of the mass balance of tracer gas in the duct is used to determine the air flow rate through the duct. This integral formulation takes the form of a scalar equation (see Part V, Section 2.3). To determine the air flow rate through the duct, one needs to know the volume of tracer gas injected rather than time history of the injection rate. Similarly, one needs to know the integral of the tracer gas concentration response and not necessarily a temporal profile of this concentration. This concentration integral can be determined numerically, based on the measured concentrations, or directly, by determining the average concentration over the period beginning before the injection and continuing until the concentration decrease to its pre-injection value. The average concentration can be determined by simply filling an air sample container at a constant rate over this period and analyzing the concentration in the container after the test.

The single-zone pulse technique is similar to the duct pulse technique in that a short duration injection of tracer gas is released in the volume being tested and the concentration response is monitored. An integral formulation of the mass balance of tracer gas in the zone is used to determine the air exchange rate of the zone. This integral formulation again takes the form of a scalar equation. As in the case of the duct application, one needs only to know the total amount of tracer gas injected and the integral of the concentration within the zone. This integral can be determined by sampling the air continuously over the integration period. The integration period need not include the time during which the tracer gas is injected and there are circumstances for which this would be advantageous.

The single-zone application of the integral pulse technique is based on the following assumptions: the tracer gas concentration within the volume being tested is uniform, the tracer gas injection rate is small compared to the air exchange rate of the zone, and the air exchange rate during the measurement is relatively constant.

The multizone integral pulse technique is an extension of the single-zone approach to several zones and enables the air flow rates between the zones and from each zone to the outside to be determined. In this application, there is a separate pulse injection of tracer gas into each zone and the concentration response of each zone is monitored in all of the zones of the system. In the multizone case, the integral mass balance of tracer gas yields a system of equations.

The measuring technique can be applied with a single tracer gas by injecting tracer gas into each zone successively. The use of multiple tracer gas enables the injection of tracer gas into more than one zone at a time, thus shortening the length of time required for a measurement. The integration period for each injection may or may not include the injection period, depending on the circumstances of the test and the characteristics of the airflow system under investigation.

Aside from the experimental and analytical procedures, the manner in which a particular building system is represented by a series of well-mixed zones is crucial in obtaining reliable measurements. The development of such a multizone representation is by no means obvious or straightforward, but it is extremely important. The multizone application of the integral pulse technique is based on the following assumptions: the tracer gas concentration within each zone is uniform, the tracer gas injection rate is small compared to the system air flow rates of the zone, and the air flow rates during the measurement are relatively constant.

Equipment

The equipment requirements of these measurements are similar to those for any tracer gas measurement technique. Air sampling equipment is required for the tracer gas concentration response determination.) For real-time monitoring, this equipment requires a system of pumps and air sample tubes to bring air from the zones being tested to the tracer gas concentration measuring equipment. The determination of average concentrations requires a constant flow pump and air sample containers. The air sampling equipment must be selected with consideration given to the number of air sampling locations and the number of zones being tested. In general, there must be several air sampling locations in each zone to verify that the tracer gas concentration within that zone is uniform.

Tracer gas concentration measuring equipment is also required for these air flow rate measurements. If real-time concentration monitoring is employed, then this equipment must be on-site. If average air samples are used, the equipment can be located elsewhere. In multizone applications, it is generally recommended that the equipment be located on-site. The important features of the concentration measuring equipment include the range of measurable concentrations and the frequency at which air samples can be analyzed. A tracer gas injection system is also required to inject the pulse injections to the appropriate locations. Such a system requires a source of tracer gas, a means of controlling its injection, a distribution system, and a means of measuring the total volume of tracer gas associated with each pulse injection.

6.3. Single Tracer, CCTG Instruments

6.3.1. The Princeton CEES Constant Concentration Tracer Gas System

CCTG Measurement Technique

Constant Concentration tracer gas (CCTG) systems have been developed by research laboratories in many of the IEA countries. The advantage of this approach with respect to multizone and interzone air flow applications is that by keeping the tracer concentration constant, in each of the many zones being tested, injection rate of the tracer is then needed only to compensate the dilution caused by air entry from outside these zones.

Typical of the CCTG systems is the IBM compatible PC-controlled 10-zone system employed by Princeton University Center for Energy and Environmental Studies *[Harrje, Dutt, Bohac, Gadsby, 1985]*. A direct descendant of the Danish system *[Collet, 1981]*, this system currently uses a single tracer gas, sulfur hexafluoride. The CCTG system is a "closed loop" operation in that it feeds back information on the measured concentration in each zones. This feed back is used to regulate the injection of the tracers in order to keep the tracer concentrations at or near the target concentrations. If interzone information is required and only one tracer is being used, discontinued injection (concentration decay method) to selected zones can be used. Since this technique is restricted to 10 zones, techniques such as guarded zone and surrounded sampling should be employed with the CCTG when used in large buildings containing many zones. *[Bohac and Harrje, 1987]*

CCTG Principles of Operation

The constant concentration technique measures the outside air flow into each zone of a building. To make this measurement, a metered amount of tracer gas is injected into each zone so that the concentration of the tracer gas is kept at a target level in all the zones. If the tracer concentration in a zone is not near the target, the measured air flow rate in that zone is in error and the air flowing from that zone causes the measured air flow rates in the adjoining zones to be in error. To compute the rate of tracer injection, a control and estimation algorithm is applied which considers the present and past level of the measured concentrations, the past injection rates of the tracer, and the estimated air flow rate *[Bohac, 1986]*.

The constant concentration system operates in two modes, these being: the start-up period, followed by the continuous response period. The control algorithm must take both these periods into account. The start-up period is modeled as a step change in the desired concentration from zero, at the initial time, to the target concentration at all subsequent times. The control design during this period is a classic servo design problem. The goal of the design is for the concentration to rapidly follow the change in the desired concentration with little or no overshoot.

During the continuous response period, the goal is to keep the concentration at the target level. This is a classic regulator problem. It can be demonstrated that a state-space analysis of the start-up period maybe used as an indicator of the form of the response of both the start-up period and for changes in air flow rate. The simulations of changes in air flow rate are used to verify the state-space analysis and to provide a qualitative analysis of the response.

To summarize, in order to maintain the tracer gas near the target level in each zone while the air flow rate is changing, the criteria to meet this condition are:

1) fast response to changes in the air flow rate with little overshoot in concentration
2) low steady state error
3) low sensitivity to measurement errors and disturbances (system noise)

CCTG - Analysis

For the analysis of the data, each zone is treated separately. It is assumed that the concentration of the air flows between the zones is at the target level. Thus, the tracer injection rate responds only to changes in zone infiltration rate and not interzone rates. Since the concentration in the zone does not stay exactly at the target, the computation method considers both the tracer concentration and tracer injection rate data. This is accomplished by performing a least squares regression analysis of the data over the specified time period. Instrument error has generally proven to be of the order of 2%. But as with any tracer measurement system that must rely on mixing within the zone to be near perfect, 10% accuracy is a more realistic estimate.

CCTG Hardware Description

The CCTG system consists of an electron capture gas chromatographer, a series of tracer injection valves and lines, a series of tracer sampling lines from each zone, an auxiliary pump to draw in the samples, valve control electronics and a microcomputer-based data acquisition and control system with appropriate software. A typical operational sequence would be:

- the concentration of a single zone is measured
- the sample valve of the next zone is opened
- the estimated concentration, the air flow rate, and injection rate are computed
- the new information is displayed on the monitor and saved to disk file
- tracer gas is injected to all zones almost simultaneously (this feature simulates steady injection greatly aiding the mixing process)

The tracer concentration measurements each take less than 30 seconds using a back flush and molecular sieve approach in the gas chromatographic procedure.

At 1990 prices, this package of equipment costs approximately $30,000 including gas chromatographer, computer, software, and injection and sampling modules. Ten zones are currently measured but more zones can be added; however, as more zones are added, the measurement time needed to analyze all zones increases, thus increasing deviations in the zone concentrations from the target value.

6.3.2. EMMARA: The Automatic CCTG Instrument of the LNE

Introduction

In the last 10 years, the *Laboratoire National d'Essais* (LNE, National Testing Laboratory) has conducted many air renewal measurements, mainly as expert testimony for litigation involving questions of ventilation *[Launey and Rabourdin, 1989]*.

The decay method was used first. This method only gives limited information on air renewal as far as air flow directions between rooms are known.

Because of these problems, the LNE has developed an apparatus for air infiltration measurement in multizone buildings using the Constant Concentration Tracer Gas method (CCTG) *[Couston, Launey, Rabourdin, 1989]*. This apparatus is called **EMMARA** for "Equipement Mobile de Mesure Automatique de Renouvellement d'Air" (Mobile equipment for automatic measurement of air renewal). It is adapted for automatic on site measurements for buildings with up to eight rooms or zones and for periods of eight days or more.

Principle of operation

The principle of operation is a single tracer gas (N_2O) using the constant concentration method. The tracer gas concentration is maintained at the same concentration in each room. The gas injection and the gas concentration are controlled by the EMMARA in each room.

The apparatus consists of a computer, an infrared gas analyzer and eight identical pneumatic segments. Each segment is sequentially scanned by the computer every 270 seconds.

The characteristic of this instrument is that the tracer is continuously injected in each room and the air of each room is continuously sampled. This task is accomplished in each room by using an individual pneumatic segment.

Data storage: All the data are stored on the hard disk of the computer. They are also sent to 8 analog outputs or by phone to another computer.

Safety: A safety system was developed for the safety of inhabitants when the apparatus works automatically during long periods.

Injection and sampling in the individual rooms:

Three modes of injection are used. They are chosen considering three criteria:

- required accuracy
- inhabitants in rooms or not
- known information on air flow directions

first mode:

injection: at the back of a mixing fan
sampling: in the middle of the room
stability: gas concentration ± 1%, tracer flow ± 10%

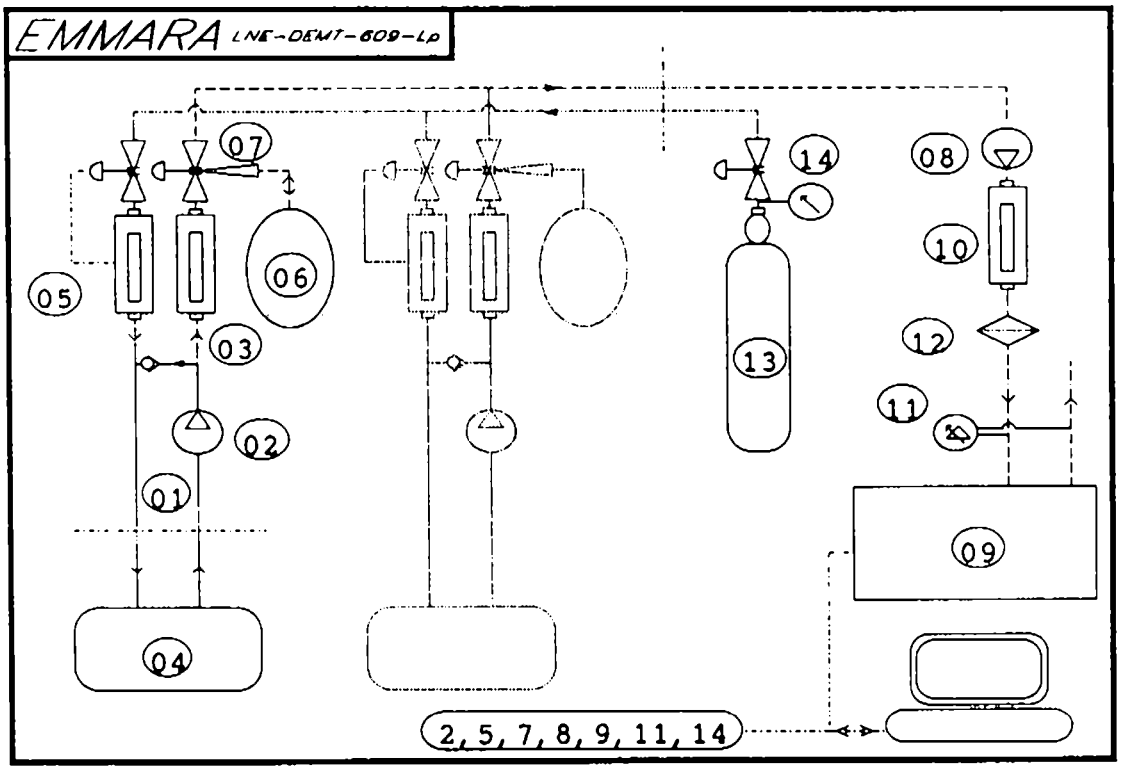
second mode:

injection: with 4 plastic pipes linked to 4 columns. Each pipe has twenty 0.5 mm diameter holes (no mixing fan).
sampling: with the same system used for injection
stability: gas concentration ± 2%, tracer flow ± 25%

third mode:

injection: near an air inlet (no mixing fan).
sampling: near an air outlet
stability: gas concentration ± 7%, tracer flow ± 100%

Description of one pneumatic segment:



1: pipes
2: pump
3: flow-meter
4: room
5: mass flow-meter/controller
6: balloon
7: valve
8: pump
9: analyzer
10: flow-meter
11: pressure gauge
12: filter
13: tracer gas
14: safety valve

Two plastic pipes (1), a pump (2), and a flow-meter (3) are used to take 300 liters of air per hour from the room to the EMMARA then back to the room (4). This system gives to the EMMARA "instantaneous" information about variations occurring in a room even if it is far from the apparatus.

The mass flow-meter/controller (5) is used to deliver a known tracer gas flow in the room.

A two liter balloon (6) is used to store air while the pneumatic component is waiting to be scanned by the computer. The balloons are used to subdue the effects of tracer gas heterogeneity in rooms.

An electric valve (7) is used to fill or to empty the balloon.

The balloons are emptied with a pump (8), connected to the tracer analyzer (9). The flow is controlled by a flow-meter (10) and a pressure gauge (11) connected to the EMMARA.

Control principles: the control algorithm must:

- reach the wanted gas concentration in a short time
- keep constant concentration despite significant variations of air change rate
- induce slight variations of the tracer gas flow

We do not use a proportional-integral-differential control algorithm because parameters of this type of algorithm depends on the air change rate. We use a transient single zone model and mass conservation during a given period. Quite simple hypotheses can be used because "immediate" accuracy is not required. The control algorithm is the following:

Parameters: C tracer gas concentration (-)
s flow of tracer gas (Nm^3/h)
n air change rate (-)
V Volume of the room (m^3)

Basic equation:

$$dC/dt = s/V - n\,C$$

At time $t_i = t_{i-1} + \Delta t$

measurement of the tracer gas concentration C_m

evaluation or the air change rate n_m for a period $N\,\Delta t$ long. (hypothesis: N steady states)

$$n_m = \frac{\Delta t \sum_{k=1}^{N} s_{i-k} - V\,(C_m - C_{i-N})}{V\,\Delta t \sum_{k=0}^{N-1} (C_{i-k})}$$

evaluation of the amount of gas tracer s_i needed to reach the gas concentration C_0 at the next time $t_i + \Delta t$:

$$s_i = \frac{n_m\,V}{1 - \mathrm{Exp}(-n_m\,\Delta t)}\,[C_0 - C_m\,\mathrm{Exp}(-n_m\,\Delta t)]$$

injection of s_i

$C_i = C_m$, $n_i = n_m$

proceed to the next time step.

With this control algorithm, the desired gas concentration is reached in less than one hour.

When the air infiltration flow decreases by 50%, the control algorithm stabilizes the gas concentration in less than thirty minutes with an overshoot of 3%.

Hardware and software description

Tracer gas: Nitrous oxide (N_2O) is used.

The purpose is to measure air change rate with inhabitants in rooms so we have investigated what are the highest usable gas concentration. There is some evidence that nitrous oxide will present no problem below a concentration of 450 ppm in volume *[Sharer, Nunn, Royson and Chanarin, 1983]*.

The gas concentration used depends mainly on:

- the sensitivity of the analyzer
- the sensitivity of the mass flow controller device
- the number of rooms
- the duration of the study
- the air change rate

For studies in eight rooms, for a period of eight days, with a maximum air change rate of 5, a gas concentration of 100 ppm is used.

Injectors:

Mass flow controller devices are used (one for each room). One mass flow controller device consists of a mass flow meter (hot wire anemometer) and a control valve. A calibration is done for N_2O.

Each mass flow controller has an input/output device:

input: desired injection rate
output: effective measured injection rate

Type: RDM 280 of Air Liquide Alphagaz

maximum flow: eight mass flow controller devices are used

1 x 1000 Ncc/mn (Nominal cubic centimeter/minute)
1 x 300 Ncc/mn
6 x 100 Ncc/mn

accuracy: ± 1% full scale

control efficiency: ± 0.25% full scale

response time: less than 2 seconds for 98% of scale

Sampling:

pumps: diaphragm pumps are used at a flow rate of 300 liters/hour

pipes: polyvinyl chloride pipes (inner diameter: 6 mm) are used. The system is designed so that these pipes are compatible with our process (no significant problems of gas adsorption or absorption).

balloons: two liter rubber balloons normally employed for artificial respiration.

Analyzer:

A non-dispersive Hartmann & Braun type URAS 3G infrared N_2O analyzer is used.

scales: 0-50, 0-125, 0-350, 0-800 ppm in volume

accuracy: ± 1% full scale

response time: less than 5 seconds for 98% of scale

induced drift: 1% full scale per week

linear change in sensitivity: 1% full scale per week

Control system:

the control system consists of:

- an IBM PC compatible Computer GOUPIL G5 with hard disc and 8 MHz clock
- a computer front end FLUKE HELIOS 1 with high performance A/D converter, thermocouple and DC volt scanner, digital I/O assembly and analog output
- electric and electronic hardware manufactured by the LNE, featuring the safety control, starting of the measurements and valve control.
- software developed by the LNE in MICROSOFT QuikBASIC 4.5 language. The system is menu driven and produces files compatible with MICROSOFT EXCEL.

6.3.3. NIST Automated Air Infiltration and Ventilation Measurement System

The Center for Building Technology of the National Institute of Standards and Technology has developed an automated air infiltration and measurement system for large building applications. This system consists of an IBM compatible PC microcomputer, an electron-capture gas chromatographer, tracer gas injection system and air sampling pumps. This system is currently being used for indoor air quality and ventilation studies in large office buildings. Two specially designed interface cards have been designed and manufactured by NIST to interface the electron capture gas chromatographer with the IBM compatible PC.

The electron capture detector is a variable frequency/constant current detector which has a wide dynamic range (approximately 4 orders of magnitude). This GC is operated usually in the back flush mode which reduces interference with other electron capture substances found in large buildings (usually Freon). The GC has a temperature-controlled oven and a ten port multi-sample value which allows the monitoring of tracer concentrations in up to 10 locations. The system can control tracer injection in up to 7 zones.

The system can allow the hardware to operate in either the tracer decay mode, constant injection or constant concentration. However, software has been developed only for the decay and constant injection mode of operation.

In addition to monitoring and controlling the injection of tracer in a multi-zone building, the system monitors external environmental conditions, interior temperatures (10), the status of HVAC system fans (up to 8) and the pulses from up to 5 pulse meters (such as electric or gas meters).

The system can operate unattended for periods of up to 5 weeks.

6.4. Multi Tracer, Pulse or Decay Instruments.

6.4.1. BRE Multi-tracer Multizone Air Exchange Rate Measurement Systems

Introduction

The origins of the techniques and equipment described here lie in the challenge to measure infiltration in large, multicelled and naturally-ventilated buildings, at a time (1979) when this problem had been almost totally neglected both because of its difficulty and an absence of appropriate techniques.

Theoretical analysis of the problem of measuring interzonal air movements and a review of existing tracer gas methods *[Perera, 1982; Perera, Walker, Hathaway, Oglesby, Warren, 1983]* suggested that two techniques should be further developed:

- multiple tracer gas
- constant concentration.

The advent of relatively cheap microprocessor-controllers opened up the possibility of automated systems able to control accurately a complicated sequence involving tracer gas release, sampling of air from several locations and recording of analyses. These tasks would be too difficult to perform manually. The basic elements of the systems developed have emerged as common to all such systems, as described in Chapter 4.

Three systems have been developed at BRE, and these are briefly described below. The first two systems presented were designed to measure interzone air exchanges using several tracer gases in 'decay' mode, one designed for installation in very large buildings, and the other a modular system particularly suitable for smaller buildings (such as houses). The third system is a constant concentration system suitable for installation in either small or large buildings.

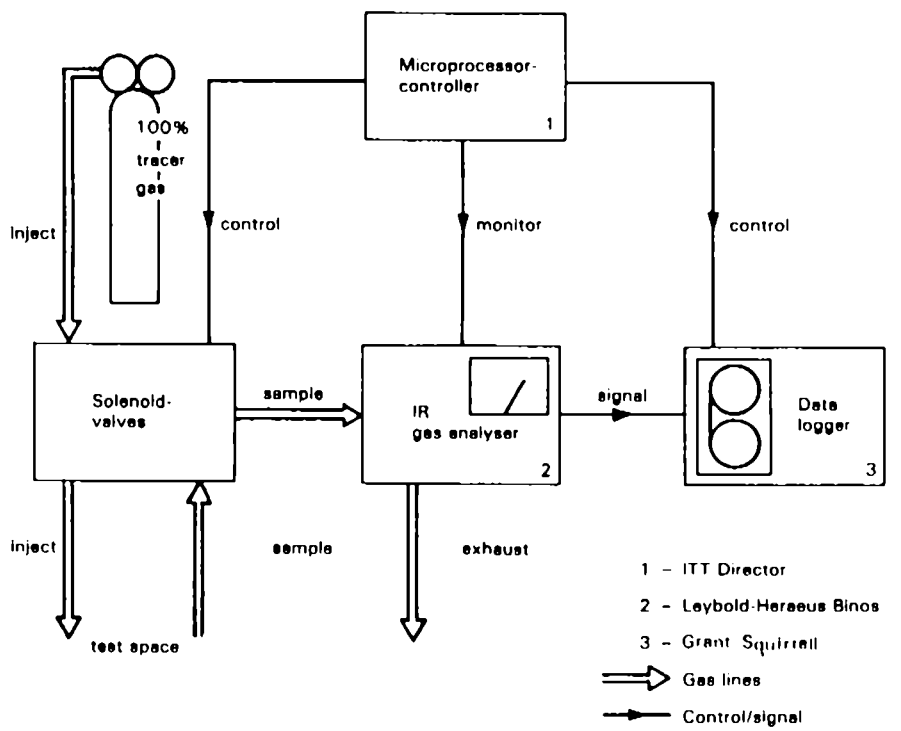


Figure 6.3: Modular system for multizone air exchange rate measurement using three tracer gases ('Decay') [Walker, 1985].

Multi-tracer 'Decay' Systems

The two systems developed follow the same operating principles, but employ hardware of different degrees of sophistication. Their use in naturally and mechanically ventilated office buildings and a house has been reported *[Perera, Walker, Oglesby, 1983; Perera, Walker, Trim, 1983, Walker, 1985]*. The main features of each are as follows:

Modular system

This system comprises interconnecting self-contained modules (fig. 6.3), and is designed to be easily-assembled, easy-to-use and turn-key operated.

Tracer gases (a maximum three) from compressed/liquefied sources (gas bottles) are delivered under pressure to the various zones through 6 mm bore nylon tubing via an injection unit containing solenoid valves. A pump draws air samples from all zones through a similar arrangement of tubing and one or more sample units (four sample lines each) containing solenoid valves. Air is returned through the injection network, thus flushing out the residual tracer gas. The sample units sequentially divert air samples from each zone to one or more analyzers, as necessary to analyze each of the tracers used. A self-contained data-logger monitors the analogue output from the analyzer(s). A programmable logic controller, controls the injection and sampling units and also synchronizes the data-logger. Alternatively a simple, but less flexible, rotary timer unit can be connected.

System for large buildings

The system for large buildings (fig. 6.4) differs in the following ways. A microcomputer maintains overall control and records data through an interface to a single flexible microprocessor-controlled multicomponent infrared analyzer and a large-bore gas-line sampler and injector unit. The analyzer can be programmed to analyze up to ten different gas components, at concentrations in the very low parts-per-million range. It has a gas cell of 5.64 liters which requires a large sampling flow rate to enable rapid analysis (6 sec per component plus 9 sec overhead), and for this reason 10 mm bore tubing is used in conjunction with a vacuum pump.

Injection and Sampling strategy

In each case the following applies:

- tracer gases are simultaneously delivered, one to each zone,
- initial target concentration achieved and delivery stopped
- achieve and maintain a homogeneous mixture of air and tracer within each zone by some means
- air samples sequentially drawn from each zone
- tracer concentrations in each sample analyzed and recorded over 30 to 60 minute test period.

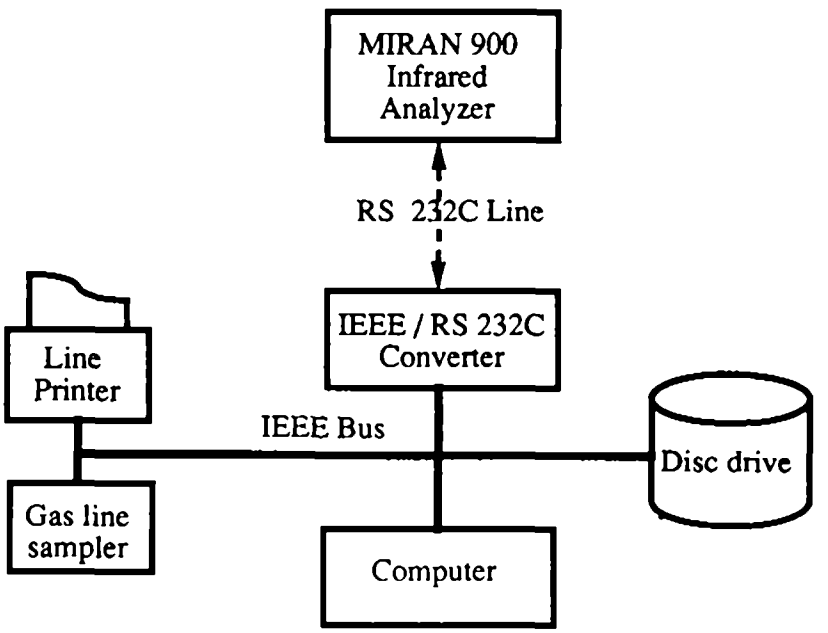


***Figure 6.4:** Multizone, multi-tracer 'Decay' air exchange rate measurement system for large buildings.*

Data Analysis

The mass balance equations for tracer gas and airflows between the zones and to the outside are formulated assuming perfect mixing and neglecting small changes in density. These are then solved for the airflows in either of two ways:

(i) at an instant in time, using measurements of the concentrations and rates of 'decay' of each tracer in each zone, or

(ii) over a short period of time, over which the equations are integrated, using measurements of the net change in concentration and the area under the curve of concentration vs. time for each tracer in each zone.

The problem is configured as a system of simultaneous equations *[Perera, Walker, Oglesby, 1983]*, which are solved for the airflows by Gaussian elimination. A least-squares procedure *[Perera, Walker, Trim, 1983]* may be applied to constrain the solutions to have positive solutions. An error analysis is carried out *[Walker, 1985]*.

Equipment

The details of the salient items of equipment for each of the two systems are as follows.

Modular system

- tracers: N2O (200 ppm), SF_6 (50 ppm) CO_2 (5000 ppm) and refrigerant $R_{13}B_1$ (50 ppm)
- analyzer: dual tracer non-dispersive IR, Leybold Heraeus Binos
- data logger: 13 channel, 12-bit, Grant Squirrel
- controller: programmable logic controller, ITT Director
- valves: 6 mm bore, 3-port, 240 V solenoid, MAC.

Large buildings system

- tracers: SF_6 (15 ppm), Refrigerants $R_{13}B_1$ (50 ppm) and R_{114} (115 ppm)
- Analyzer: microprocessor-controlled, multicomponent IR (optical filters), Miran 980
- Control and Data logging: Commodore CBM micro-valves: 12.7 mm bore, 3-port, 110 V solenoid, MAC.

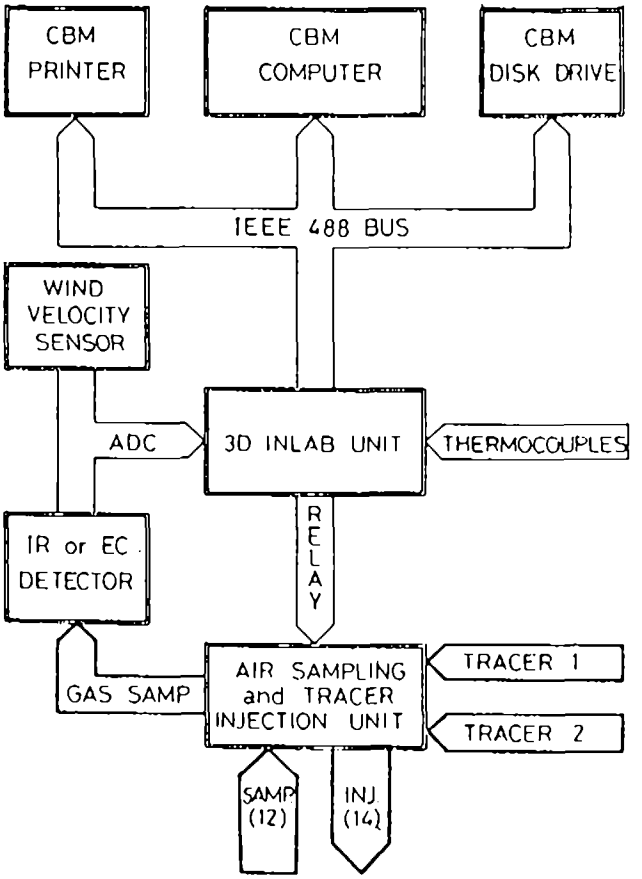


Figure 6.5: Constant concentration system for infiltration measurement in multicelled buildings, schematics [Perera, Walker, Hathaway, Oglesby, Warren, 1983]:

Constant concentration system

This is a microcomputer controlled system (fig. 6.5) capable of maintaining a constant concentration at twelve sample locations. It has been used to measure infiltration rates in an office room in a fully

occupied four-storey naturally-ventilated office building *[Perera, Walker, Hathaway, Oglesby, Warren, 1983]*.

Principle

A constant concentration of tracer is maintained in the zone(s) of interest (test zone) and also in all surrounding zones with which significant air exchanges may occur;

- the injection flow rate (when required) is closely maintained at a set value using high quality gas regulators and needle valves, and regular checking with a soap film meter;
- rapid-response solenoid valves ensure a steady injection flow rate is quickly achieved over short injection times;
- in the test zone, the injection times are summed over a suitable period (e.g. one hour) and used to compute the fresh air infiltration into that zone during the period.

Equipment

- tracer gases: SF_6 (e.g. 5 ppm), N_2O (0-200 ppm), refrigerant $R_{13}B_1$ (0-50 ppm)
- valves: rapid response (3 ms), micro-solenoid valves (Lee Products Ltd)
- analyzer: non-dispersive infrared, Leybold Heraeus Binos
- controller: Commodore CBM micro.

6.4.2. Parallel Column System (PCS) for the Measurement of Air Flows Between up to Three Zones

Introduction

The development of the PCS became necessary when it was realized that a simple, single chromatographic separation column could not analyze air samples containing three tracer gases within a sufficiently short time interval to enable the preferred mathematical analysis to be used successfully, whilst maintaining a satisfactory level of tracer gas peak resolution at low tracer gas concentrations.

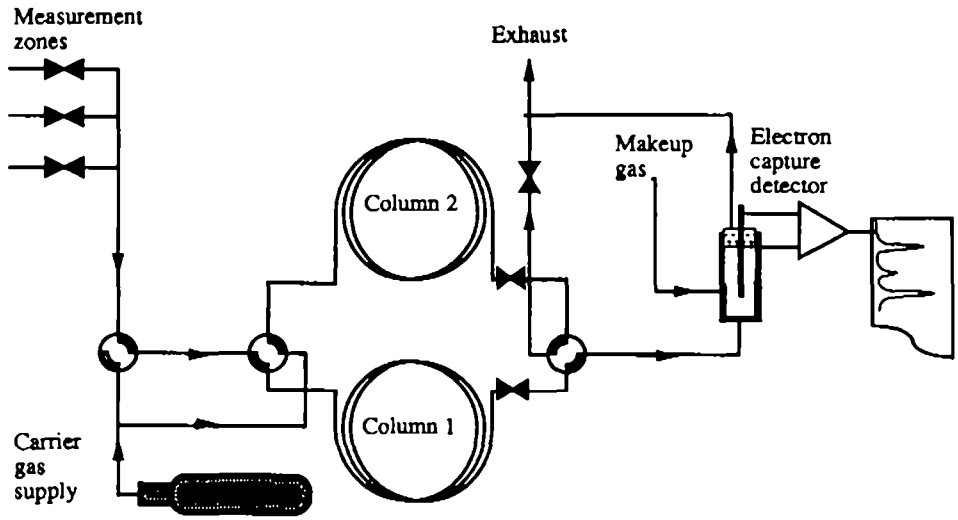


Figure 6.6: PCS system schematics [Irwin, Edwards, Howarth, 1985].

Principle of operation

The technique is of the decay type. Tracer gases are injected manually into each cell. Mixing is effected by the use of 400 mm diameter oscillating desk top fans. Good mixing is generally achieved

within five minutes. Samples are drawn from each cell by means of a small pump, and are introduced into the PCS by means of a manual sampling valve.

The PDS is fitted with an electron capture detector (ECD). Two gas chromatographic separation columns are connected in parallel to the ECD. Using three tracer gases, an air/tracer gas sample can be analyzed in 30 seconds. The rapidity of sample analysis is achieved by making use of the "dead time" associated with the passage of a sample through a separation column *[Irwin, Edwards and Howarth, 1985]*.

Interzonal air flows are calculated by a mathematical analysis which involves the solution of the fundamental conservation of mass of tracer gas equations. The solution is simplified by the omission of recirculation terms *[Irwin and Edwards, 1987]*. It has been shown that in the vast majority of circumstances, recirculation effects will not exert a significant influence over measured tracer gas concentrations for the first twenty minutes of a decay-type test: this means that, providing sufficient data points can be taken during this period, then the omission of the recirculation terms is valid.

Hardware and software description

The three gases used are Freons 12, 114 and BCF, although the feasibility of replacing the tracers with more "ozone friendly" substitutes is being evaluated. Typical concentrations would be in the range 1 to 10 parts per million.

The PCS is based upon the Analytical Instruments Model 505 portable gas chromatographer. The gas chromatographic separation columns used are of 6 mm internal diameter, and 3 meters length.

The packing is 10% squalane on a zeolithe (non acid washed) base. In order to ensure the best possible response match between the columns, the columns are conditioned prior to use, and are immersed in a thermostatically controlled water bath/stirrer unit at a temperature of 30°C during operation. The four point valves are made by Whitey. The separated samples are analyzed by means of a Ni-63 electron capture detector.

The instrument is capable of detecting tracer gas concentrations of as low as parts per billion, although the preferred operating range is of the order of low parts per million. Tracer gas concentrations in excess of 12 ppm will "saturate" the ECD and are thus avoided.

Tracer gas concentrations are currently output to a chart recorder. The use of a Squirrel data logger as a recording device is currently being assessed.

6.4.3. Parallel Detector System (PDS) for the Measurement of Air Flows Between Four or More Zones

Introduction

The PDS system is a further refinement of the PCS described earlier. The development of the PDS became necessary when it was realized that the PCS could not analyze air samples containing four or more tracer gases within a sufficiently short time interval to enable the preferred mathematical analysis to be used successfully, whilst maintaining a satisfactory level of tracer gas peak resolution at low tracer gas concentrations *[Edwards and Irwin, 1987]*.

Principle of operation

The technique is of the decay type. Tracer gases are injected manually into each cell. Mixing is effected by the use of 400 mm diameter oscillating desk top fans. Good mixing is generally achieved within five minutes. Samples are drawn from each cell by means of a small pump, and are introduced into the PDS by means of a manual sampling valve.

The PDS is fitted with two electron capture detectors (ECD), which are capable of being operated both simultaneously and independently. Two gas chromatographic separation columns are connected in parallel to each ECD. Using four tracer gases, an air/tracer gas sample can be analyzed in one minute: this means that the PDS can receive one air/tracer gas sample every thirty seconds, since the use of parallel detectors doubles the available time for which detector output can be monitored for a given sample. This extra time reduces the urgency for rapid tracer gas peak throughput, and hence improves peak resolution at lower tracer gas concentrations.

Interzonal airflows are calculated by means of extending the analysis used for three interconnected cells to the case of four interconnected cells *[Edwards, Irwin, 1987]*.

Hardware and software description

The four tracer gases currently preferred are Freons 13B1, 12, 114 and perfluorocarbon PPI, although the feasibility of replacing the three Freons with more "ozone friendly" substitutes is currently being evaluated. Typical concentrations of tracer gas would be in the range 1 to 10 parts per million. The PDS is based upon the Analytical Instruments Model 505 portable gas chromatographer. The gas chromatographic separation columns used are of 6 mm internal diameter, and 3 meters length. The packing is 10% squalane on a zeolithe (non acid washed) base. In order to ensure the best possible response match between the columns, the columns are conditioned prior to use, and are immersed in a thermostatically controlled water bath/stirrer unit at a temperature of 40°C during operation. The four point valves are made by Whitey. The separated samples are analyzed by means of two Ni-63 electron capture detectors.

The original signal amplifier/invertor board within the AI505 unit has been replaced by a custom-made twin channel board. The instrument is capable of detecting tracer gas concentrations of as low as parts per billion, although the preferred operating range is of the order of low parts per million. Tracer gas concentrations in excess of 12 ppm will "saturate" the ECD's, and are thus avoided.

Tracer gas concentrations are currently output to a twin-channel chart recorder. The use of a Squirrel data logger as a recording device is currently being assessed.

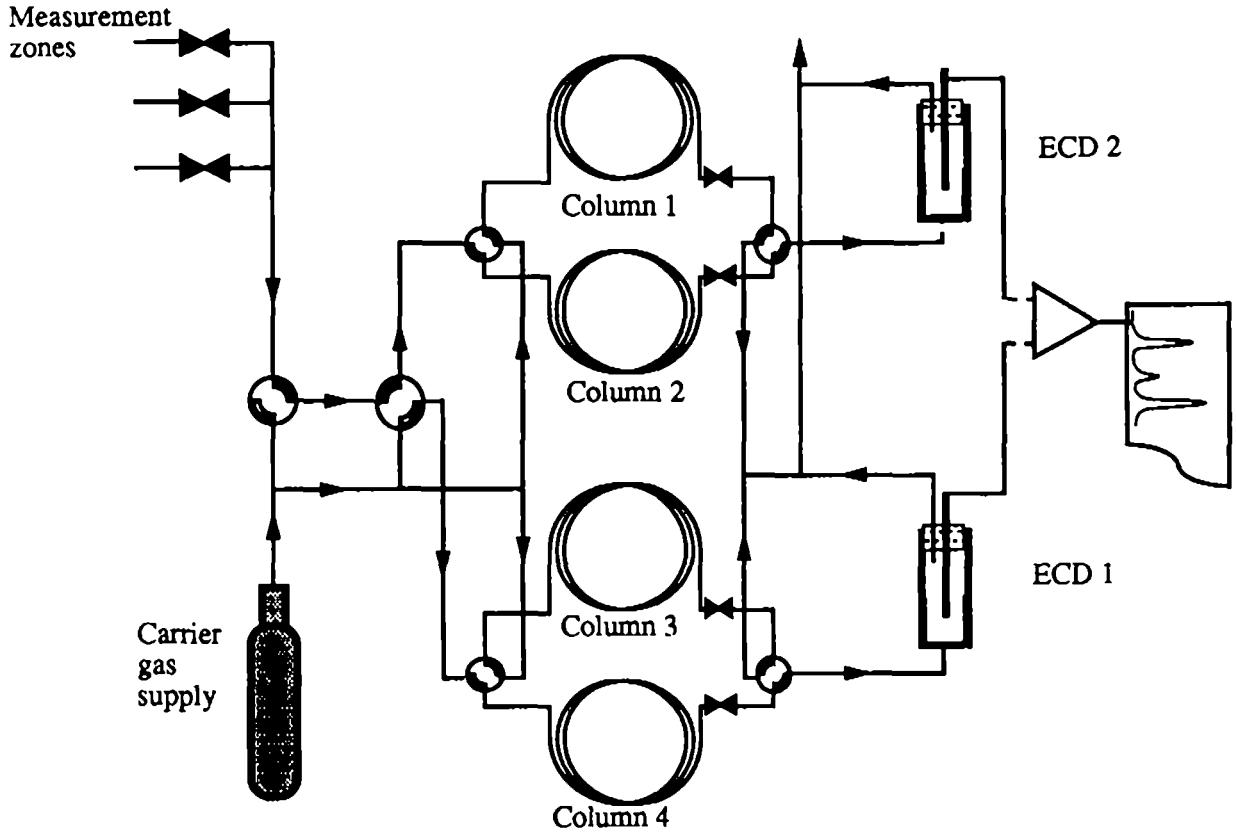


Figure 6.7: PDS system schematics [Edwards and Irwin, 1987].

6.4.4. Multi-tracer Instrument from Brüel & Kjaer

Introduction

In 1979 a project was launched at the Technological Institute, Copenhagen with the purpose of developing a method for continuous measurement of air change rates in occupied dwellings. 10 years later, in 1989, we have introduced the first generation of mass-produced equipment performing measurements of air change rates employing the method of constant concentration of tracer gas *[Grieve, 1989]*. The principles used in the first model, which was introduced in 1981 at the Technological Institute, are largely identical to those used in the latest model from Brüel & Kjaer.

However, the basic components and the microcomputer programmes have been changed several times and, through the years, new programmes have been developed that expand the capability of the measuring equipment.

Among the most important improvements - introduced in 1988 - was the use of multi tracer gases when making measurement, so that interzonal air flows could be measured.

Principle of operation

The primary function for the measuring equipment is to maintain a constant concentration of one or two tracer gases in between 6 and 12 rooms, to register how much tracer gas is dosed in each room, and to measure the concentration of tracer gases in the rooms. Furthermore, the equipment can be set up to give a user defined constant dose in some or all of the rooms.

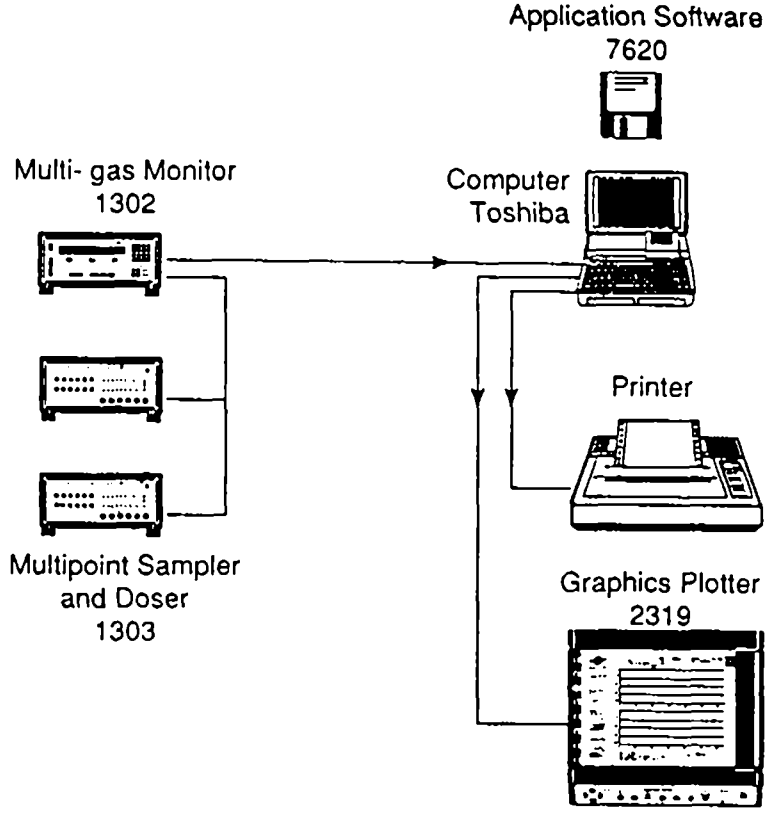


Figure 6.8: Composition of the equipment [Brüel & Kjaer Company 1989].

The main function of the computer is to control the "dosing" of tracer gas from the "doser" part of the 1303 to each of the rooms in which air-change analysis is being performed, and to control the "collection" of air samples from each of the rooms by the "sampler" part of the 1303, which sends them sequentially to the 1302 for analysis. The other important function of the computer is the collection and storage and analysis of measurement data from the 1302 and 1303 (s). Stored data are presented in both graphical and listed form.

The Multi-gas Monitor Type 1302 measurement principle is based on the photoacoustic infra-red detection method *[Cristensen, 1990]*. In effect this means that the 1302 can be used to measure almost any gas which absorbs infrared light. Appropriate optical filters (up to 5) are installed in the 1302's filter carousel so that it can selectively measure the concentration of up to 5 component gases and

water vapor in any air sample.

Each of the two Multipoint Sampler and Doser Type 1303's can be supplied with an individual tracer gas. This means that one tracer gas can be dosed into 6 rooms, and that an alternative tracer gas can be dosed into 6 other rooms.

The sampler system of the 1303 has 6 inlet channels, each with a solenoid valve. The 6 inlet channels converge into one; a three-way valve can then direct the gas sample to the 1302 for analysis, or through the pump to the waste air outlet. A pressure transducer checks the efficiency of the sampling pump and allows checks for blocked airways.

The doser system of 1303 has 6 outlet channels, each with a solenoid valve. Each channel has a nozzle which reduces the internal diameter of the channel. The design of the nozzles ensures that the rate of flow of tracer gas to the dosing points is dependent only upon the tracer gas supply pressure and temperature, and is unaffected by the pressure in the dosing tubes or at the dosing point itself (supersonic nozzle).

Two separate inlet channels serve the dosing tubes: the tracer gas inlet, and the carrier air inlet. The tracer gas inlet channel is pressurized by the tracer gas supply cylinder. The carrier air inlet pumps extra air to the dosing tubes to speed delivery of the tracer gas to the dosing point.

The dosing system can deliver a continuous dose, that is, an uninterrupted flow of tracer gas over a period of time; or a discontinuous dose, in which the amount of tracer gas delivered is reduced by interrupting the flow at regular intervals during the dosing period.

The 1303 can calibrate each dosing nozzle automatically, so that the amount of tracer gas delivered during a dosing procedure can be accurately determined by the 1303.

Specification

The measuring system uses non diluted tracer gases. Usable tracer gases are: SF6, N2O, R-12, R-13B1 and R115.

The repeatability of the monitor is 1% of the measured value.

The measuring range for SF6 of the gas monitor is 0.05 ppm to 500 ppm, and the uncertainty of concentration measurements at 1 ppm is approx. 3% of the measured value; all assuming that the monitor has been calibrated during the last month and that the uncertainty of the concentration of the calibration gas used for this calibration is less than 2.0%.

Measuring time per point is 45 sec. when the concentration of two gases is to be registered.

Accuracy of dosage calculation in the 1303 is ±2%. The maximum dose rate of tracer-gas amount from one 1303 is 27.5 ml/sec. This means that air changes of up to 100,000 m3/h can be measured if the concentration in the rooms is maintained at 1 ppm.

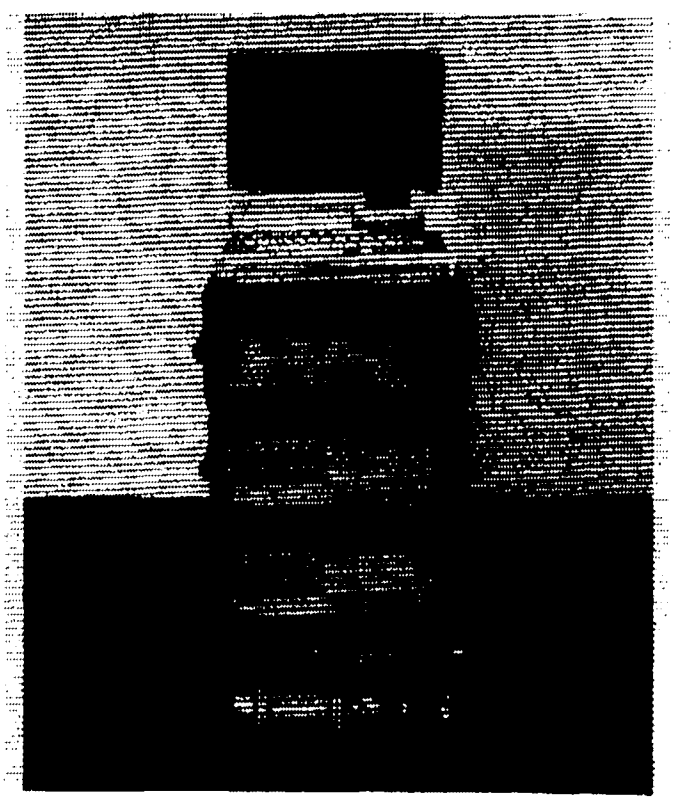


Figure 6.9: The equipment for measuring with two tracer gases is composed of:
1 Brüel & Kjaer Type 1302 Multi-gas Monitor
2 Brüel & Kjaer Type 1303 Multipoint Sampler and Doser
1 Brüel & Kjaer Type 7620 Application Software
1 Toshiba T1600 or IBM PS2-50 computer
Photo Brüel & Kjaer

6.4.5. A Multi-tracer system with variable internal sampling.

Introduction

The concentration decay technique is widely used for the measurement of air flow in buildings *[Lagus and Persily, 1985]*. This technique involves the injection of a known amount of tracer gas into a building followed by a period of mixing to establish a uniform tracer concentration. The decay of tracer gas is then measured. In the case of air flow measurements made between two zones, the variation of tracer gas concentration with time depends on the size of the doorway and on the temperature difference between the two zones. Recent work has indicated that the accuracy of air flow estimation is strongly influenced by the number of samples taken during the transient period *[Riffat, in BSRT, 1989]*. This is the first 2-10 minutes of the measurement when then the concentration of tracer gas is varying most rapidly. Tracer gas decay systems which are currently available do not have sufficient flexibility to provide accurate measurements of air movement through large openings as their sampling/analysis times are too long (typically 3-4 minutes) to allow a sufficient number of measurements to be taken during the transient period. Clearly there is a need to develop a new system which allows a large number of tracer gas samples to be taken at intervals as short as 5 seconds during the transient period and a small number of samples at intervals greater than 5 seconds during the remaining period.

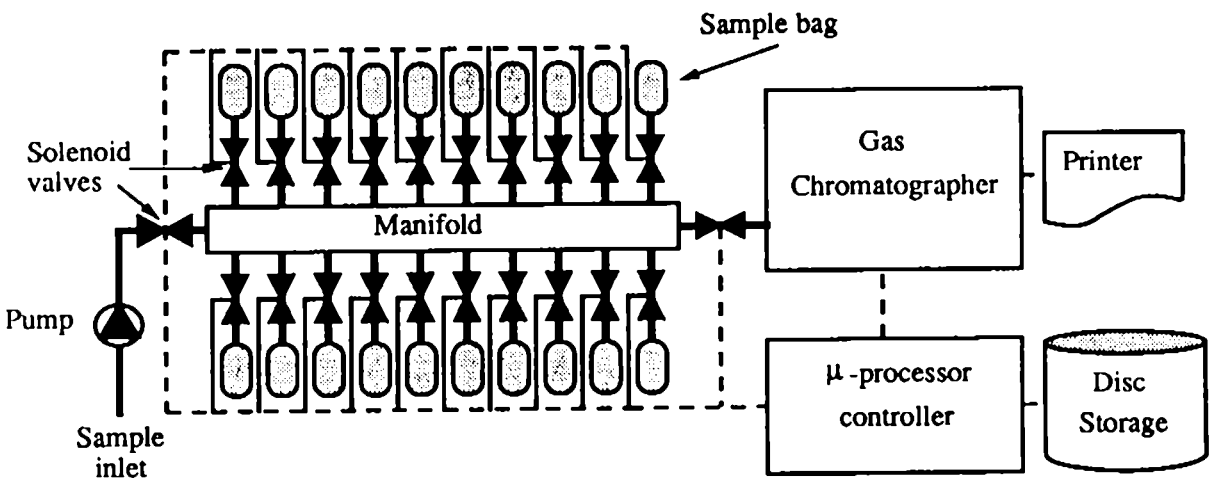


Figure 6.10: A multi-tracer gas system with variable interval sampling [from Riffat].

Principle of operation

The automated sampling system is shown in Figure 6.11. The sampling speed of the system can be adjusted so that a large number of tracer gas samples can be collected during the transient period of an measurement and a smaller number during the remaining period. This technique minimizes the error in the term dC/dt (where C is the concentration of tracer gas and t is time) and hence allows an accurate estimation of air flow rate to be made *[Riffat, Vancouver 1989]*.

The tracer gas system is flexible and could be used for on-site analysis or for grab-sampling. On-site analysis involves connection of the sampling system to a portable gas chromatographer so that tracer gas samples can be injected directly into a chromatographer. Grab sampling involves the collection of tracer gas samples for subsequent analysis in the laboratory using a more sophisticated gas chromatographer. In this case, more than one tracer gas could be used in each measurement.

In order to measure interzone air flow, a sampling system is placed in each zone. Different tracer gases are then released, one gas in each zone, using automatic injection units. After tracer gas release and mixing, samples are collected and analyzed in the laboratory. The sampling system is designed to collect as many as 40 samples from a zone at intervals appropriate to the measurement. In a typical measurement the system would collect about 30 samples during the transient period (at 5-10 second intervals depending on the size of the opening and the temperature difference) and about 10 samples (at intervals greater than 10 seconds) during the remaining period.

Hardware description

The microprocessor-controlled tracer gas system is capable of taking samples at intervals as frequent as every 5 seconds. In essence, the tracer gas sampling system incorporates solenoid valves, tracer gas sampling bags, a pulse pump, a microprocessor-based controller, a manifold and a by-pass valve. The

short sampling period is achieved using a specially designed microprocessor controller. This contains a central processing unit and programme memory with a capability of 60 input/output.

The portable chromatographer consists of a 6-port valve connected to a 0.5 ml loop, a column, a chromatographic oven and an electron capture detector. The system incorporates a microcomputer, a parallel printer and interface cards for both analogue and digital data. The system could be used for sampling various tracer gases. We chose to use sulphur hexafluoride (SF6) and perfluorocarbons (PFTs) as they have desirable characteristics in terms of detectability, safety and cost. In addition their suitability has been demonstrated previously by their successful use in other air movement studies *[Riffat, Eid and Littler 1987, Dietz and Cote, 1982].*

Tracer gases are released automatically using portable and free-standing units. The perfluorocarbon release system consists of a small cylinder wrapped with a heating mat and fitted with a pressure relief valve. The SF6 release system consists of a small SF6 cylinder, a pressure regulator and a solenoid valve. The solenoid valve is normally closed but can be opened automatically using the microprocessor. The volume of tracer gas released depends on the size of the building and is controlled by adjusting the length of time that the valve is open.

6.5. Multi Tracer, CCTG or CITG Instruments.

6.5.1. MTMS: The LBL Multigas Tracer Measurement System

Introduction

Detailed air flow measurements require complex, multizone tracer gas strategies. Although single gas strategies can be employed in many instances, only multigas capabilities are appropriate for determining an entire matrix of air flows. The Lawrence Berkeley Laboratory, Energy Performance of Buildings Group has developed a multigas tracer system for multizone air flow measurements based upon the use of a mass spectrometer to provide real-time measurement capability of time-varying interzonal flows *[Sherman, and Dickerhoff, 1989].* This MTMS system has been employed in both single family and multi family buildings to determine the flow rates between zones and between each zone and the outdoors. Its measurement results were compared to those of other instruments in several buildings *[Harrje, Dietz, Sherman, Bohac, D'Ottavio, and Dickerhoff, 1990]*

MTMS Principles of Operation

MTMS, like all tracer gas ventilation measuring systems, uses the dilution (or non-conservation) of a tracer gas to infer air flows. In order to do this, the system must be able to perform certain functions: injecting controlled amounts of tracer gases into specified zones, measuring the concentration of the tracer gases in all the zones, and storing the resultant information for later use. MTMS is able to do these functions using a PC-controlled data logging and control system. Air sampled from each zone is sequentially introduced into a Residual Gas Analyzer (RGA,i.e., a quadrupole mass spectrometer) which measures the intensity of selected peaks that uniquely identify and quantify the concentration of all the tracers in each zone. At present five tracer gases have been used successfully and a capability of eight has been demonstrated in the laboratory. In order to keep concentrations within acceptable limits, MTMS attempts to keep the concentration of each gas at a constant value in the zone in which it is injected. Since (in contrast to the CCTG system) the analysis is not dependent on holding constant concentration, the control is optimized for stability rather than fast response.

Under perfect conditions, almost any method of injecting the tracer gasses into the zones would lead to a good estimate of the air flows; but the accuracy and precision of the air flow calculation depends on many factors: instrument capabilities, relative size of air flows, mixing, the conditioning of the concentration matrix, etc. The purpose of the control algorithms in MTMS is to minimize the uncertainty in the data analysis by suitable control of the injected flow. The control strategy used in MTMS is an attempt to minimize errors due to several different sources as follows:

a) Instrumentation Accuracy: The precision of the injection and concentration determination is usually an absolute value expressed as a percentage of full scale. To minimize the impact this uncertainty has in the calculation, it is desirable to maximize the signal.

b) Mixing: When tracer is injected into a perfect zone, it is completely and instantly mixed. In a real zone it takes some time for the measured concentration to reflect the zone average concentration. This kind of mixing effect can be reduced by keeping a steady injection and concentration within the zone rather than allowing the zone concentration to fluctuate. (Other types of mixing effects such as stratification, dead zones, short-circuiting, etc. require careful sampling design and cannot

be dealt with by the control strategy.)

c) Matrix conditioning: The analysis method includes the inversion of the concentration matrix. Uncertainties in the measured quantities and numerical errors will be amplified if the concentration matrix is ill-conditioned. (The best conditioned matrix would be diagonal; the worst would have a zero determinant.) Although the conditioning of the concentration matrix will be to some extent limited by the conditioning of the problem (i.e., the air flow matrix), the control strategy should seek to keep the concentration matrix well-conditioned.

The MTMS control strategy is a compromise between these objectives. A single, unique tracer gas is injected into each zone. Thus, the concentration of that gas in that zone will be largest; if there were no air flow between the zones this would lead to a perfectly conditioned concentration matrix. Given that it is not possible to inject a negative amount of tracer gas, this strategy leads to a maximally well conditioned concentration matrix. For a single tracer to be injected into each zone a target concentration is chosen so as to maximize the dynamic range of the instrumentation and thus minimize the instrumentation-induced errors.

The control algorithm used in MTMS is a type of proportional-integral control scheme that separately controls the injection of each tracer gas based on the concentration of that tracer in the zone in which it is injected.

MTMS Hardware Description

The MTMS hardware is responsible for measuring the concentrations of all gases in all zones and for injecting tracer gases into those zones in order to effect the control strategy. The core of the system is the measurement of concentration and it is supported by plumbing and control technology. Total cost for the hardware alone (not including fabrication labor) was about $33,000 (1989 prices).

Currently, Residual Gas Analyzers (RGAs), quadrupole mass spectrometers, are small, reliable, and available at prices comparable to gas chromatographers.

Air coming into an RGA is ionized and the resulting positive ions are separated by their charge-to-mass ratios and directed at an electronmultiplier for detection. Separation is achieved by directing the ions axially between four rods and varying an electric field on the rods at radio frequencies. When a new air stream is selected it must flush out the ionization area before its concentration can be measured.

The sample air pressure must be reduced to that required by the RGA. A multistage reduction in pressure is necessary to meet the pressure requirements. The first reduction is achieved by flow resistance within a small capillary tube. This reduction is limited to the pressure at which molecular flow is induced. The pressure is further reduced by expansion into a small chamber from which a small portion is allowed to expand into the RGA via an orifice, the bulk of the gas is pumped away with the vacuum fore-pump. This process limits the response time by the travel time in the capillary and the flushing of the expansion chamber with the fore-pump. Including the valve manifold, the overall response time of the MTMS hardware is about one second.

The RGA itself has an absolute accuracy of about 1/2% of reading; however, at the pressures we are working there is electronic noise of about 20 ppb. Most tracer gases can be calibrated to ± 1% down to 2 ppm where the noise dominates the uncertainty. Gases with a large background concentration in air may have to be used at higher concentrations to maintain the same uncertainty, (e.g.helium at 5.25 ppm background concentration will have a minimum uncertainty of 53 ppb). The electron multiplier is less sensitive to heavy ions and so it is necessary to use slightly higher concentrations for gases such as sulfur hexafluoride. For MTMS gases the typical target concentration (i.e.the concentration in the zone in which they are injected) are from 20 to 50 ppm to allow the non-target concentrations to be measured with some accuracy.

Injection of Tracer Gas

The tracer gas injection is controlled by a separate Mass Flow Controller (MFC) for each gas. These devices measure the mass flow with a precision hot wire anemometer (or hot films) and control a needle valve to regulate the mass flow to within 1% accuracy (full scale) in a 50:1 operating range. These specifications are often exceeded in practice where one can sometimes get a 70:1 range and better low end accuracy. Response time is typically under 10 seconds, occasionally some adjustments are necessary to the controls when changing gas type or flow range.

6.5.2. CESAR: Compact Equipment for Survey of Air Renewal

Introduction

The described apparatus measures the air change rates using three tracer gases and was built on the basis of the experience gained with a single-tracer CCTG instrument *[Scartezzini, Roulet, Jolliet, 1985; Roulet and Scartezzini, 1984 and 1987]*. Up to 10 locations can be measured simultaneously either by the decay method, the constant flow or the constant concentration method, the latter being particularly developed and the most used. The analyzers are non dispersive IR spectrometers, the tracers being N_2O, SF_6 and Halon R1301. The complete equipment can be transported.

Principle of operation

The controller is a MS-DOS compatible personal computer. It monitors the programmable sampler and injector and logs the measured data. A control program is designed to inject the right quantity of tracer gas in such a way that a constant concentration, which is not hazardous even for long time exposure, is obtained.

The control method used in the program is a digitized and modified PI (proportional-integral) which can achieve a very stable concentration, even when the air flow rate changes strongly. The control parameter are chosen in an optimal way and do not depend much on the air flow rates *[Compagnon, Kohler, Roecker, Roulet, 1988]*. Overshoots are avoided by non linear modification of the control algorithm (see Section 4, appendix 2 for more details).

The air flows are also computed off line and are displayed by the controller, taking into account the residual small variations of the concentration of the tracer, the cross sensitivity of the analyzers and the variations of the density of air. The interpretation uses the zone-by-zone systems of equations.

Hardware and software description

This equipment has the following parts:

1- Four non dispersive infrared spectrometers (BINOS of Leybold Heraeus company), one tuned for water vapor and the others for the three tracers used: nitrous oxide (N_2O, 200 ppm fsd†), sulfur hexafluoride (SF_6, 20 ppm fsd) and Halon 1301 (R13B1, 20 ppm fsd). The necessary correction on the tracer concentration due to the presence of water vapor is automatically performed. Other analyzers may be installed with minor modifications. Once analyzed, the sample is flushed outdoors.

2- An 11 channel programmable sampling unit (developed at the LESO), the eleventh channel being the outdoor air. This sampler contains the sampling pumps and sets of electrovalves enabling the sampling of the rooms in an arbitrary sequence. While the air of a given room is sampled and injected into the analyzer, the sampler pre-pumps the sampling duct of the next channel. The analyzing time is short enough to scan 11 channels (e.g. 10 rooms and the outdoor air) in less than 10 minutes.

3- A 10 channel programmable tracer injection unit (also developed at the LESO), which can inject, in any sequence, one of the three tracers in a duct leading to a room. Each channel has two supersonic nozzles, adjusted for two different flow rates. The control of the injected quantity is achieved by electrovalves controlling the injection time through the chosen nozzle. The tracer injected in the duct is then flushed with outdoor air, while the unit injects another tracer in the duct connected to the next room.

4- A process controller (an MS-DOS operated PC) and a data processing unit (Hewlett Packard 3852A). These control, by means of the CESAR software, the time-shared injection and sampling sequences and the data logging.

5- An anemometer to record on site the simultaneous values of wind direction and speed.

6- Temperature sensors (Pt 100 Ohm) to measure the indoor and outdoor temperatures.

Two programs are used with this system:

CESAR is the controlling code, mainly developed for the constant concentration method. It is written in Quick Basic for MS-DOS. It performs the automatic control of the programmable injector and sampler, and logs the measured data in the mass memory (hard or floppy discs). The input of the measurement parameters (i.e. volumes of the rooms, sequence of the injections and measurements, etc.) is menu driven and user friendly. It can also, as an option, monitor the decay method, which is

† fsd for full scale deflection.

mainly used to measure the local or room mean age of air.

AUBE interprets the data files created by CESAR and gives the results in a numerical form. This program, written in Fortran 77 uses the equations presented in § 4.4.1 of Part III, allowing density variations *[Roulet and Compagnon, 1989]*. Resolving of the system of equations is undertaken zone by zone, non existent flows are hence not calculated. A Bayesian technique is used for error analysis. The results of this program can be examined graphically with the help of a graphic code in use at the LESO.

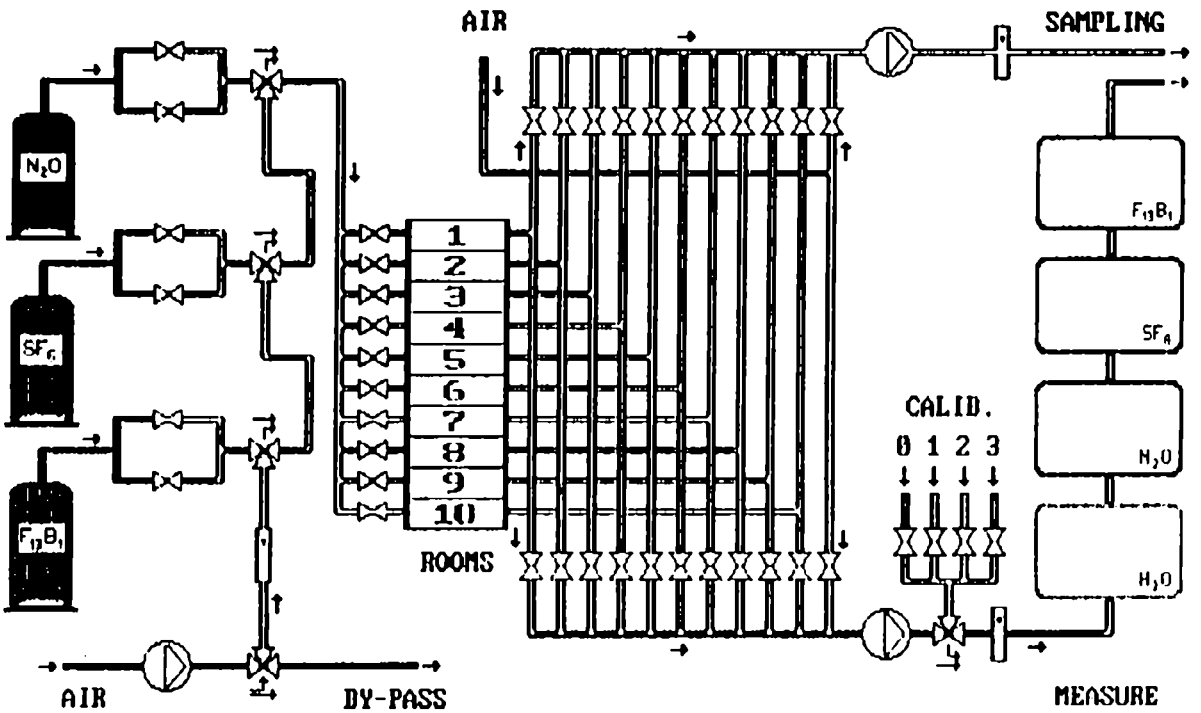


Figure 6.11: Schematic layout of the CESAR instrument, as it appears on line on the screen of the controller, to show a synoptic color picture of the system. The travel of the tracers and purging air, as well as the measured concentrations and temperatures are displayed.

6.5.3. MATE: Multipurpose Automated Tracer gas Equipment

Introduction

The MATE system was developed in 1987-1989 primarily for measuring air flow rates by using tracer gas in 60 naturally ventilated ducts but with the requirement of being general enough to allow other kind of tracer gas measurements *[Wouters, Vandaele, Bossicard, Voordecker, 1990]*. Applications which are already being performed or are planned for the near future are:

- measurements of flow rate, humidity level and CO_2 level in 60 natural ventilated ducts with a sampling time of some 20 seconds per duct, *[Wouters and Vandaele, 1990]*
- measurement of pollutant distribution within an enclosure (50 measurement points within the enclosure) using 2 tracer gases,
- measurement of radon levels, CO_2 levels and N_2O levels in buildings with high radon contamination.

Principle of operation

The system is not being developed for any single application. It means that the principle can vary as a function of the application.

The type of components is the same as used in some other systems. Specific attention went to the requirement of short measuring cycles since up to 60 channels must be measured in a reasonable time.

A number of basic routines exists but no general software usable for all envisaged applications is available or planned in the short term.

Hardware and software specifications

The basic components of the system are:

- 6 programmable MATE-boxes, developed at BBRI, allow each of them to inject tracer gas in 10 zones and to take air samples in 10 zones. Each box can only inject 1 type of tracer but the 6 boxes together permit the injection of a maximum of 6 different tracers
- the controller is an IBM-PC compatible machine with 'viper'-card which enables the use of programs written in HP-basic. An HP Vectra with viper card is normally used.
- the data acquisition system is an HP3852
- a pump system continuously extracting air from all sampling points permits a substantially reduced measurement time per point
- one or more infrared gas analyzers (CO_2, N_2O,...) characterized by a very short reaction time (time constant of less than a few seconds). The analyzers for CO_2 (0-5000 ppm) and N_2O (0-500 ppm) are both from Servomex
- one or two programmable MASS-boxes (Multipurpose Automated Sampling System), developed at BBRI, enabling the measurement of up to 20 pressure differences per box with a whole range of options with respect to the reference pressure.
- the controlling code is written in HP Basic. The implementation of control algorithms for constant concentration are planned for the medium term.

6.5.4. The BNL and CEES Perfluorocarbon tracer (PFT) Measurement Technique

Introduction

Perfluorocarbon tracers provide the multitracer capabilities needed for multizone and interzone flow measurements. The developments of the PFT concepts by Brookhaven National Laboratory have resulted in a family of measurement systems *[Dietz, Goodrich, Cote, Wieser, 1986]*. The PFT gas source has centered on the use of miniature permeation sources for each of the individual PFT types. Based on gas chromatographic analysis, up to seven PFT gases have been uniquely detected in laboratory tests, and three to five gases have been routinely used in a variety of field studies in single and multifamily buildings.

In many of these studies, PFT concentrations at a given building location, have been measured with a passive integrating sampler for extended periods, weeks or even months, to estimate average air exchange rates. The passive sampler has been applied routinely in measurement periods as short as six to 12 hours. Where shorter-term air flow data are required (e.g., as little as 15-minute periods), active short-duration programmable sampling, or even real-time measurements can be made. The variety of PFT measurement equipment includes a real-time portable gas chromatographer that was originally designed for airborne service to measure PFT concentrations released from ground sources (such as power plants), an automated measurement system taking samples over predetermined time intervals and known as BATS (Brookhaven Atmospheric Tracer Sampler), and the most widely used technique of passive sampling that relies on passive adsorbent tubes known as CATS (Capillary Adsorption Tube Sampler). CATS and BATS require a laboratory gas chromatographic system to determine the PFT concentrations.

PFT Principles of Operation

The advantage of using PFTs is that these tracer gases are almost absent from the background in our indoor or outdoor environments. Therefore, using sensitive gas chromatographic electron capture detectors, measurements of concentrations used are nominally in the 1 to 30 parts per trillion range. This means small quantities of tracer needed and cost savings in the testing; e.g., a 20-story, 200,000 m^3 building would require less than $ 10 of PFT for one year of testing *[Dietz, 1988]*. One would like a series of PFT gas types that are distinct from each other, yet are able to be analyzed quickly. Four of the PFTs being used can be analyzed with a GC cycle time of about eight minutes; if five are used, the

total analysis time is typically 13 minutes. The laboratory GC cycle consists of sampler desorption, precut column separation and catalytic treatment of unwanted constituents with retrapping of the PFTs, followed by desorption, additional catalytic treatment, drying, separation and detection.

In a typical field study the sources are distributed in each of the zones to be tested. Although the source emission rate is temperature dependent (involving about 4% per degree C increase), tests have shown no bias in the results as long as the true average source temperature is used to calculate its rate. To maintain a constant production rate, commercially available temperature-controlled source holders can be used, but with a resulting order-of-magnitude increase in the source cost. Typically, CATS would be placed in each zone away from PFT sources and so positioned that natural air movement in the room would cause the room air mixed with the PFT tracer to be present at the CATS location. If the BATS unit is deployed it would also normally operate in the zone of interest, but like the real-time system it can also sample from each zone via tubing. After each measurement period, the CATS are analyzed by the gas chromatographer; the concentrations for each PFT in each zone indicate both the magnitude of dilution from outside air (air infiltration rate) into each zone and the amount of air exchange to and from each of the other zones.

PFT Analysis

The method of air flow analysis used by BNL inserts the measured tracer concentrations and known emission rates from the sources into a multizone model consisting of $N2$ mass balance differential equations and $2N+1$ flow balance equations, where N is the number of well-mixed building zones. With passive sampling (CATS), the equations are solved assuming steady-state prevails (i.e., the derivatives are set equal to zero). With concentration sampling as a function of time, obtained from programmable sampling using BATS, the derivatives within the mass balance equations are evaluated using a five point numerical technique around the point of interest. Errors on computed flows are estimated using a first-order error analysis technique. A further description of the techniques used by BNL to calculate ventilation flows and their errors from the concentration measurements can be found in *[D'Ottavio, Senum, Dietz, 1987]*.

Hardware Description

Field Equipment: The BNL passive sources are aluminium shells 32 mm long x 6.6 mm inside diameter, which are flared slightly to facilitate the insertion of oversized silicon rubber plugs (12.7 mm long x 7 mm diameter). The shells are then lubricated, swabbed with a solution of 5% silicone grease in ethyl acetate, and air-dried in an inverted position to concentrate the lubricant at the opening. A code number is engraved onto the shell for identification of the PFT source, silicone rubber plug type and number of the source.

The shells are filled with exactly 0.4 ml of the appropriate PFT liquid, using an automatic pipette. The pre-cut plugs are inserted, pressed flush with the end. The cost is about 8 dollars per source (1990 prices).

The passive sampler, CATS, is a Pyrex glass tube 6.4 mm diameter, 6.4 cm long with rubber end caps, one of which is removed during the test period. The tubing is selected to have an ID within ± 1.5% of the design value; the length is cut to within ± 0.8 mm. This tolerance is necessary to keep the sampling rate, which is proportional to the cross-sectional area and inversely proportional to the length from the mouth of the glass tube to the surface of the adsorbent bed, within ± 3% precision. The glass tubes are cleared using a detergent solution and given a unique identification number.

Within the tube, held in place by 150 mesh stainless steel screen, is exactly 64 mg of a charcoal-like adsorbent, Ambersorb, in the form of tiny spheres which capture the PFT tracer. This adsorbent is put through a conditioning process before being used as a tracer sampler. It is initially boiled, three times, in distilled water, and any fine dust floating on the surface is decanted off. It is then dried and rolled down a very shallow, inclined plane to separate any shapes which are not nearly perfect spheres. Finally, it is boiled again until the decanted fluid is clear, dried and sieved to a 30-to-50 mesh size.

After initial fabrication of the sampler it is made ready for its first use by being thermally desorbed at 425-450 °C for 10 minutes. The ends are then sealed with specially fabricated polyurethane rubber caps.

Cost is about $ 7 per sampler at 1990 prices. Both the sources and passive samplers are commercially available.

The BATS programmable sampler contains 23 metal tubes each filled with Ambersorb. Each tube in the lid of the BATS may be selected to receive the pumped air flow for a particular time period. The current commercially available BATS, as well as a new generation prototype under development, was developed for atmospheric tracer measurements and costs between eight and nine thousand dollars.

Simple,automated and programmable systems using the CATS tubes as the sample collectors have used commercially available plastic bag and syringe samplers with costs in the range of 2,000 to 3,000 dollars.

The real-time sampler/gas chromatographer may be used for in-situ indoor or outdoor air flow studies or it may be employed in the laboratory for CATS analyses. The latter arrangement involves the use of a rack to hold the CATS and auxiliary electronics. Each CATS is heated with a nichrome wire heater, forcing the tracer to leave the Ambersorb and move to the trap(s) within the real-time sampler. From there it is analyzed in much the same way as the laboratory gas chromatographer. The procedure is computerized and automatic with each CATS analyzed in turn, data then is recorded on disk and printout provided.

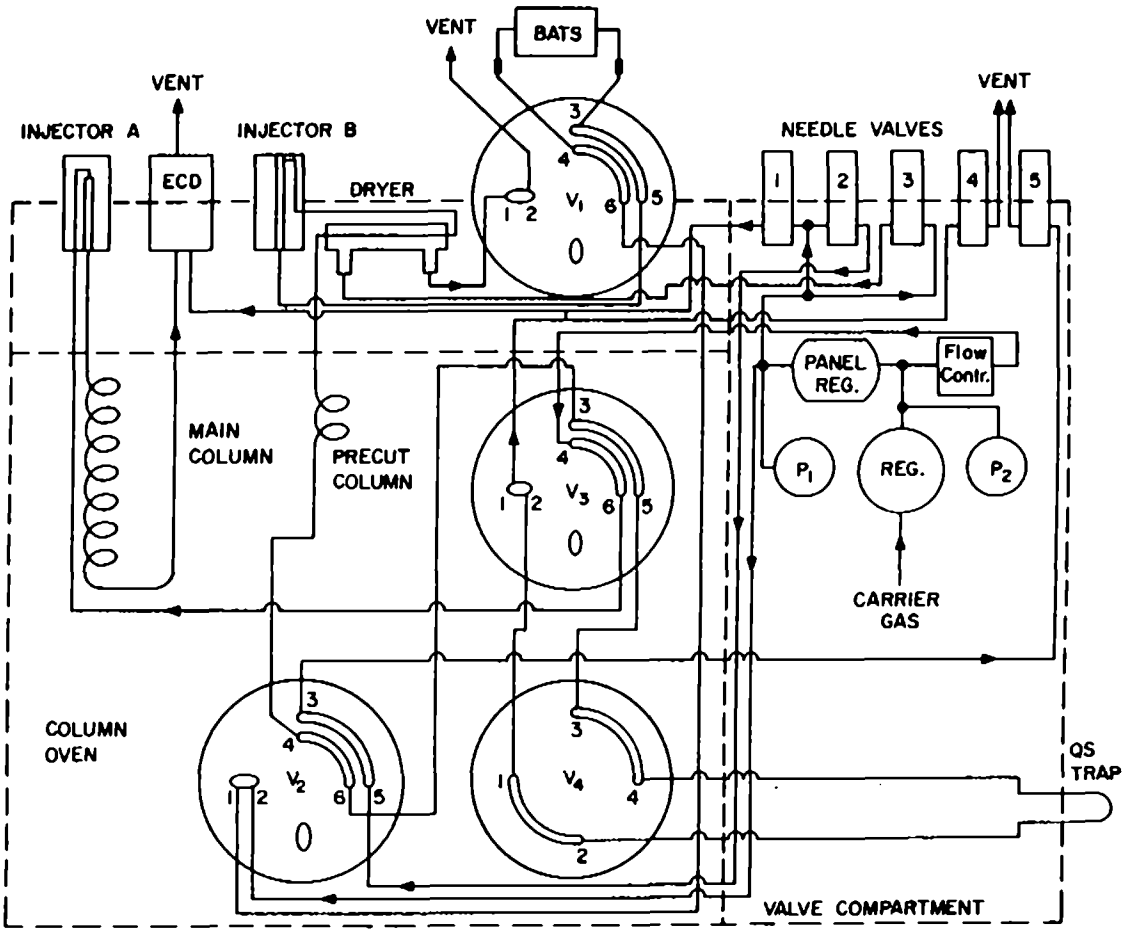


Figure 6.12: A schematic of a modified gas chromatographer assembly, used for the BNL technique [Dietz, Goodrich, Cote, and Wieser, 1986].

Laboratory equipment: The determination of the concentration of the PFTs collected by the tubes is also accomplished with a modified gas chromatographer system. The scheme includes thermal desorption, chemical and physical processing, chromatographic separation and electron capture detector (ECD) determination of the quantity of tracer recovered. A schematic of a gas chromatographer assembly, used for this technique, is shown in Figure 6.12.

The sample is automatically thermally desorbed and passed through a palladium catalyst bed and a pre-cut column before being re-concentrated on an in situ trap. The trap prevents the collection of unwanted low molecular weight constituents, and the pre-cut column prevents the passage of unwanted high molecular weight constituents. After thermally desorbing the trap, the PFTs are

separated in the main column after passing through another palladium catalyst bed and permeation dryer (to remove moisture) and detected in the ECD. Two processes occur during a single cycle; analysis of a previously collected sample and the loading of a new sample onto the trap. At the start of the cycle, the FD valve goes on as well as the Florasil trap valve (FS). Note that all the valves are shown in their "off" position; "on" means the FS valve rotor turns 90 degrees and the others, 60 degrees. Thus, when heat is applied to the FS trap, the adsorbed PFTs are flushed out through catalyst bed "A", catalyst bed "B", the dryer, the main column, and the detector (ECD). The entire process for the last PTCH isomer to elute is under 12 min; the cycle time was set for 12 min.

Prices for the real-time sampler unit start at $ 24,000. Rack, computer, software, interface components, PFT gas standards, and training bring the total cost to approximately $ 40,000. A complete laboratory PFT analysis system built around a commercial GC instrument, and including an automated GC-CATS desorption rack, PFT gas standards, data acquisition with computer and software, manuals, and system training would cost about $ 130,000, but measurement sensitivity is increased by an order of magnitude over the sampler unit. Costs are based on 1989 prices.

6.5.5 The SIB passive tracer gas method.

Introduction

The passive techniques using PFTs are well developed in Nordic countries *[Säteri, 1991]* and they rely on the same basic principles as the perfluorocarbon tracer (PFT) measurement technique developed at Brookhaven National Laboratory. Thus, perfluorocarbon tracers are released at a constant rate by diffusion from liquid tracer compounds in small containers. Sampling is also made passively by diffusion into an adsorbent contained in a narrow glass tube. The SIB passive tracer gas method developed at the National Swedish Institute for Building Research *[Stymne and Eliasson, 1991]* present details of the tracer source design and PFT analysis which are, however, widely different from the BNL-method.

Principle of operation

The passive tracer gas sources and samplers are distributed in the building to be investigated. After mixing, which takes a few hours, the samplers are decapped and left to sample the air for one week to several months. After sampling, the time is noted and the samplers recapped and sent to the laboratory for analysis. In a typical case where the total ventilation flow is of primary interest, two different tracer sources are used in conjunction with a few samplers, which are preferably located close to identifiable extract points.

PFT-analysis

At the laboratory the adsorbent is transferred to a glass vial. The adsorbed compounds are extracted with 1 ml of purified toluene. A small portion of the solution (1 microliter) is injected into a gas chromatographer (GC) where separation is achieved with a dual column system, with refocusing after the pre-column in a cooled trap. The effluents from the analytical column are measured with an electron capture detector. The total amounts of tracer compounds are quantified through comparison with the ECD signals from a standard sample. From the known sampling rates of tracer gases in the adsorption tube, the emission rates of tracers and the sampling time, the average tracer concentrations at the location of the sampling tube are calculated.

The estimation of ventilation parameters (e.g. total ventilation flow, purging flow rates, room to room air flows, ventilation indices) from tracer concentrations is performed using a multicell model with necessary simplification due to building characteristics and emission and sampling strategy.

Hardware description

At present two tracer gases can be analyzed on a routine basis (perfluro-benzene (PB) and perfluoro-methylbenzene (PMB)), while three others (PMCH, PDCH and PDCP) still require additional development of the GC separation technique to be useful for field trials.

A tracer gas source is constructed from a 1 ml glass vial equipped with a Teflon membrane. A diffusion adsorption tube consists of a standard SKC-Anasorb sampling tube, which is cut 17 mm above the adsorbent bed. The inner diameter of the opening is 4.3 mm and the sorbent bed consists of 100 mg activated carbon, and a back up layer of 50 mg activated carbon. The cost of one tube is approximately 1.2 US$. The tubes are disposed of after use.

The gas chromatographer employed is HP 8990 equipped with an automatic sampling tray (100 vials) and a commercially available column switching system (Chrompack). Preseparation is done on an 8 m wide-bore fused silica column, coated with carbowax, and final separation is done on 25 m capillary (0.2 mm) fused silica column with dimethylsilicone coating. Intermediate trapping is performed using a 20 cm dimethylsilicone coated capillary column piece, cooled with liquid carbon dioxide. The total cost of the complete laboratory equipment amounts to approximately US$ 80 000.- at 1990 prices.

6.5.6 The Automated Apparatus of the Politecnico di Torino

Introduction

The aim of the research group of "Dipartimento di Energetica" in Politecnico of Turin is to set up an apparatus for air infiltration measurement comparable to those of other IEA countries *[Borchiellini, 1983; Vacchelli, 1986; Call, Fracastoro and Vacchelli, 1986]*. At the same time, the experience developed in the theoretical studies of inverse problems (applied to heat conduction) was applied to air infiltration studies.

Apparatus description

This apparatus was designed for on-site measurements and for laboratory test. It consists of two main sub-sets of components:

- Sub-Set A (SSA): a compact and mobile multi-tracer gas system developed for multizone analysis and for on-site measurements;
- Sub-Set B (SSB): it just includes the components used in laboratory experiments in order to test the calculation technique based on the "Ill - posed problems" theory *[Beck and Arnold, 1977], [Beck, Blackwell, St. Clair, 1985]*. Since the conservation equations of the mass of tracer and the mass of air are written for a zero-dimensional model, we have decided to use small boxes, easy to build, to model different zones.

Figure 6.13 displays schematically the complete system. The sub-system A consists of:

- two infrared-photometers for the measurement of the nitrogen protoxyde (N_2O) and sulphur hexafluoride (SF_6), these are Leybold-Heraeus models Binos 1.1 and Binos 3.
- PC computer, laptop model based on Intel 80C286, 12 MHz processor; the computer controls the valves position and acquires data (tracer concentration, indoor and outdoor temperature);
- an IBM - compatible multifunction analog and digital I/O board (16 single-ended analog input channels 12 bits resolution, 2 analog output channels 12 bits resolution, 8 digital inputs and 8 digital outputs);
- an IBM - compatible digital I/O board (24 channels of digital I/O, three 8-bit groups independently selectable for I/O, connected to a solid-state relay sub-systems);
- an HP-3497A data acquisition control unit able to replace the two IBM - compatible boards;
- twelve solenoid valves (V0 - V11) to perform the sampling of air and the gas injection; the valves requires 24 V electrical supply.

The sub-system SSB is a scale model of a two-zones system; it consists of:

- two small boxes made of wood: the volumes of the first (ZONE 1) and the second (ZONE 2) are respectively 0.0525 m^3 (0.35 x 0.50 x 0.30 m) and 0.1242 m^3 (0.467 x 0.566 x 0.470 m); they are a small scale representation of two different zones connected by a pipe between the points 14 and 15 of Figure 2; each zone has three sampling points (points 1 - 2 - 3 for ZONE 1 and 4 - 5 - 6 for ZONE 2) and is connected to the external environment by a pipe equipped with a flow-meter (see points 13 and 14 in figure 2); the injection of the tracer gas and the air supply are accomplished in zone 1 only (points 10 and 12);
- two mixing fans, one for each zone;
- three flow-meters and three pumps to control the air change and verify the mass balance in each zone;

- one electric resistance to vary the air temperature;
- two platinum resistance thermometers to measure the air temperature in each zone, so that it can be taken into account in the mass balance equations.

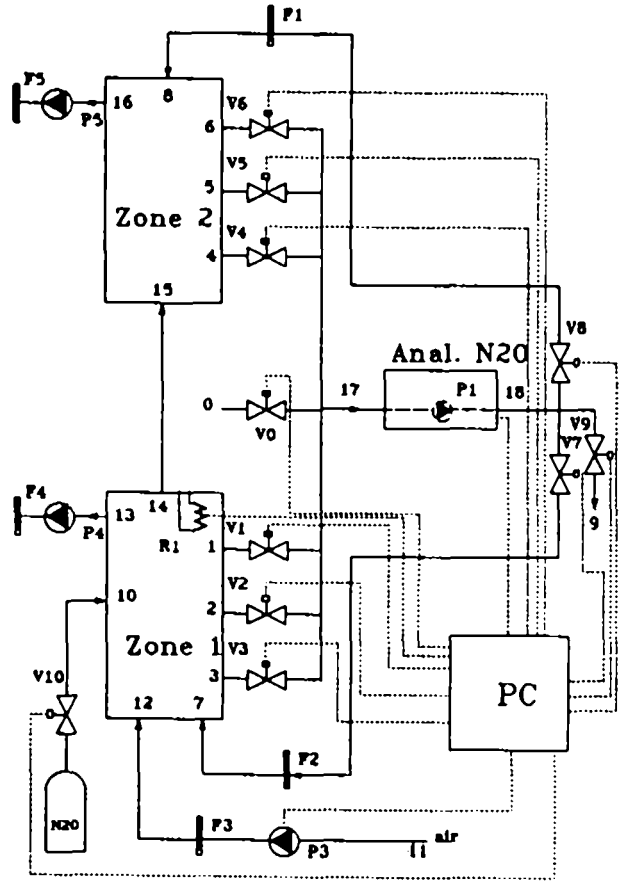


Figure 6.13: The complete instrumentation [Borchiellini and Cali, 1990]

The two sub-systems are presently used to perform laboratory tests whose main purposes are improving our experience on tracer gas measurement and obtaining the wide set of experimental results necessary to check the numerical technique chosen to calculate the air flows.

The complete apparatus is a multizone and single tracer gas system. The zones are represented by the two boxes, which are very tight as indicated by pressurization tests

A computer program interactive with the operator runs on the PC and executes all the different operations required to carry out the measurements. The program includes also utilities to set the zero and full scale points of the analyzer; the on-line calculation of the air change and of the initial tracer concentration are also displayed.

Data analysis

The quantities used in the conservation equations can be sorted in measurable quantities, y, and parameters, x. Then the equations can be written in the general form:

$$y = f(x) \tag{1}$$

The measurable quantities in our problems are tracer gases concentrations, source flow-rates, temperatures and pressures, while the parameters are volumes of each zone and air flow-rates. The estimation of the parameters x is a typical inverse problem which has been widely treated in literature. A bayesian calculation strategy is used. *[Beck and Arnold, 1977], [Beck, Blackwell and St. Clair, 1985], [Tarantola, 1987].*

This approach was applied successfully to single-room measurements; the measured data being analyzed after the end of the experiments (whole domain technique); the next step is to apply this approach to multizone measurements using either whole domain or sequential (on-line) technique.

The outcomes of the research work made up till now show that great attention must be paid to:

- the influence of the temperature difference between zones and also to temperature changes during measurements;
- the data covariance matrix, mainly when high speed acquisition system is used.

7. Comparisons of Methods

Several publications are found in the literature, which compare two or more measurement techniques used on the same object. This comparisons, which provide useful information on the accuracy of these techniques, can be sorted into two categories: tracer gas measurement on well controlled test houses and inter-comparisons of different tracer gas techniques in the field.

7.1. Measurements on laboratory test houses or test rooms.

The tracer gas measurements are performed on well controlled test houses or test rooms, generally located in a laboratory. The air flow rates in the zones of these test buildings are controlled by a ventilation system, in which the air flow rates can be measured in the ducts, using classical techniques (see Part V). The objective of such comparisons is to evaluate the tracer gas techniques for their ability to provide a good estimate of constant air flow rates.

Such comparisons were published by several authors, in particular:

Several measurements made in the test indoor house of the National Swedish Institute for Building Research are described in *[Sandberg and Blomqvist, 1985]*. Both decay and constant concentration single-tracer techniques were tested. The conclusions are that a perfect mixing is difficult to achieve in a multizone building, since the standard deviation of the mean age of air between rooms was between 10% (for an air change rate of 1.4/h) and 24% (for an air change rate of 0.3/h). The standard deviation in measured air change rates between the rooms was nevertheless smaller. Since 10 fans did not provide a better mixing than 6 fans in this 5-zone house, it is proposed to install one fan in each ordinary room with an additional fan in the largest room.

Single tracer gas, decay measurements on a two-chamber small-scale test rig are described in *[Riffat, 1989/2]*. Different interpretation algorithms were tested on unperturbed and perturbed measured data. The conclusions are given in Section 4.3.2.

Two- and three- zone decay measurements with the same number of tracers are used for a comparison between three analysis methods *[Irwin and Edwards, 1990]*.

[Enal, Shaw, and Reardon, 1990] present a similar experiment with multi-tracer techniques applied on two well controlled rooms. Their results have shown that the accuracy depends on the time at which the concentration are taken for interpretation. Therefore, they propose a technique to select the appropriate time.

[Okuyama, 1990] tested his identification methods on measurement performed in the Swedish laboratory test house. This test has shown that a minimum measurement time equal to the nominal time constant is needed to obtain a reasonable accuracy. With mixing fans, the interzonal air flow rates were under-estimated by less than 20 % while a mismatch as large as 90% was observed without mixing fans.

A series of validation experiments were carried out under controlled condition in a three-zone system, using the UMIST three-gas instrument *[Irwin and Edwards, 1986]*. The relative difference between the air flow rates measured on one hand by tracer gases and on the other hand by hot wire or Pitot tube anemometers was about 20 %, but the air change rates were found to be estimated within 10% of the true value. In these experiments, the typical time constants (e.g. the ratio of the volumes of the cells to the air flow rates) were small (much less that one hour) and the minimum measurement time required was found to be about 20 minutes.

A similar validation experiment performed at the University of Illinois *[O'Neill and Crawford, 1990]* allowed the authors to show that both air flow rates and effective volumes can be determined with a reasonable accuracy in a three zone system with a single tracer with a reasonable accuracy, provided that these unknowns remain constant for the minimum measurement period, which is, in their case, two hours.

These last two experiments seem to show contrary results, since 20 minutes are sufficient in one case when two hours are needed in another experiment to show a reasonable accuracy. In fact, they agree and confirm that the optimum measurement time period is not absolute, but depends on the typical time constants of the measured system.

A comparison of various methods for two-zone measurements was conducted as well by numerical as by experimental techniques *[Heidt, Rabenstein, Schepers, 1990]*. The numerical technique simulates the measurement by Monte-Carlo methods, and the experiments were conducted on laboratory scale

models. The authors compared a single-tracer pulse and decay method with dual-tracer decay and repeated pulse techniques. They conclude first that the eigenvalue analysis presented by *[Sinden, 1978]* and widely used afterwards by others, worked well for clean data, but produced large errors in the estimated flows when the data are corrupted with a small amount of noise (2 % or more). This confirms the results of *[Irwin and Edwards, 1986]*.

Using the inversion of the mass conservation equations and provided that the tracer concentrations are taken at proper time intervals, they found that the dual-tracer technique is convenient for short-time measurements (period of the order of magnitude of the nominal time constant or less) while the single tracer pulse and decay method can be used for longer time measurements, since it is of simpler use, provided that the ventilation remains constant.

7.2. Field comparisons of different techniques.

[Walker, 1985] presents a comparison of different interpretation methods based on the same data, measured with three tracers in a two-storey attached house partitioned into three zones. He concludes that, for decay experiments, integral interpretation on a given period of time is more accurate than a least square fit on few measurements obtained during the same period of time.

Different techniques used in the United States were compared in a multifamily building *[Harrje, Dietz, Sherman, Bohac, D'Ottavio and Dickerhoff, 1989]*. The compared techniques include a constant concentration single-tracer gas system, a multitracer gas system using mass spectrometer and perfluorocarbons (PFT) multitracer systems both passive and active. Such a field test proved to be useful to compare the effects of real-time perturbations on the measurement techniques and their results. All techniques, with the exception of passive PFT, were found to respond quickly to fast changes in air flows. It also have shown some limits to such comparisons, since first, the compared systems cannot use the same tracers and secondly, a system using one tracer at high concentration may disturb another system working at very low concentrations.

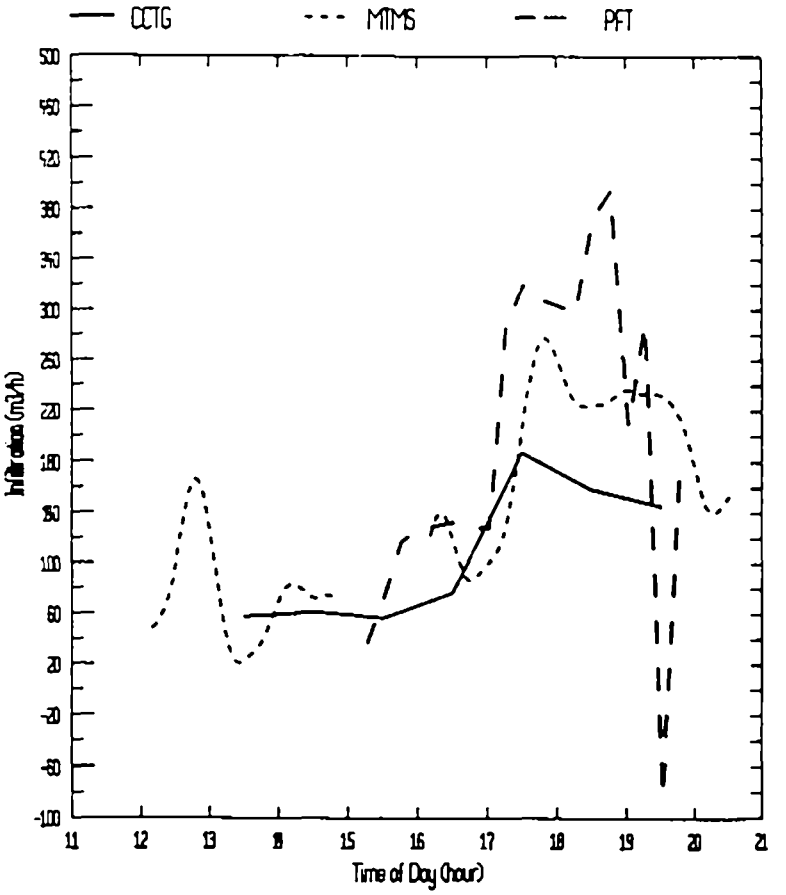


Figure 7.1: Three air flow measurement systems evaluating the fluctuating air infiltration flow rate in a zone containing a kitchen and a living room [Harrje, Dietz, Sherman, Bohac, D'Ottavio and Dickerhoff, 1989].

Figure 7.1 shows the air flow rates as measured by three active systems in a zone. This comparison shows that the results are fairly similar, but some differences can be observed. A part of the differences are attributed to the interference effects mentioned above. Another important part was found to be the result of different interpretation methods rather that of the tracer gas injection and analysis itself. In particular, the large fluctuations observed in the results of the PFT active method between 18:30 and 20:00 are because the open door between the two rooms allowed the different PFTs injected in these two connected rooms to be intermixed, which causes the systems of equations used for interpretation to become ill-conditioned. Once the two rooms merged into one zone for interpretation, these fluctuations completely disappear.

This last fact is confirmed by another study of the performance of the passive PFT method using as well laboratory measurements as field investigation *[Sateri, Jyske, Majanen, Seppanen, 1990]*. These authors emphasize the importance of a good mixing and have found that an accuracy of better than 20% can be achieved, if minimum caution is taken.

8. Standards

This chapter examines a selection of standards and regulatory documents which relate to air flow rate and air exchange rate measurement techniques. Several countries have developed standards relating to this type of measurement. Table 8.1. presents several of these standards giving for each its country of origin, governing body, designation, title, type of measurement to which it refers, and level of accuracy expected. Summaries of the standards referred to in Table 8.1 are presented below.

Country	Governing Body	Designation	Title	Method	Accuracy
Nordic	NORDTEST PO Box 111 SF 02101 Espoo	NT VVS 048	Buldings: Total Flow Rate of Air - Continuous Measurement.	CCTG	5-10 %
Nordic	as above	NT BUILD 232	Buildings: Rate of Ventilation in Different Parts of a Building	Decay	10-20 %
Sweden	BST, Drottning Kristinas Väg 73 S 11428 Stockholm	SS 02 15 56	Buildings: Determination of Outdoor Air Inflow	Decay	12-18 %
USA	ASTM 1916 Race Street Philadelphia, PA 19103, USA	ASTM E-741 83	Standard Practice for Measuring Air Leakage Rate by the Tracer Dilution Method	Decay	10 %

Table 8.1: Standards related to measurement of air flow rate.

8.1. Nordic Standard NORDTEST NT VVS 048

This document describes a standard technique for the continuous measurement of air change rate in occupied and unoccupied buildings using the constant concentration tracer gas technique. The technique can be used for continuous determination of the infiltration of outside air into an entire building or individual rooms of a building. Air change rates are determined by measuring the amount of tracer gas required to maintain a constant concentration of tracer gas in the measured enclosure. Fully automated equipment is required to make this type of measurement. Besides explaining the principles of the measurement technique this document describes the equipment required for the test, the preparation of the building under examination and the measurement procedure. The expression of the results and the accuracy of the technique are also discussed. A standard reporting format for the test is also included.

8.2. Nordic Standard NORDTEST NT BUILD 232

This document describes a standard technique for monitoring the natural and forced ventilation rate in different parts of a building. The method can be used in all types of building. Practical difficulties can limit its range of application. Problems occur mainly in buildings with large volumes and high ventilation rates. Difficulties in interpreting the results can arise when examining buildings with large interzonal air flows.

The ventilation rate is evaluated using the tracer dilution (decay rate) method. A suitable tracer gas is distributed within the volume to be evaluated, and air samples are taken for analysis from locations where the air change rate requires measuring. The decay of the tracer gas is directly correlated with the ventilation rate in various parts of the buildings.

The principle of the measurement is explained, equipment suitable for making the test is described and the measurement procedure is presented. Other sections in the document examine the preparation of the test building, the expression of the results, and the accuracy of the technique. A standard format for the test report is presented.

8.3. Swedish Standard SS 02 15 56

This standard applies to the determination of outdoor air flow into buildings. The outdoor air flow can be created by mechanical or natural ventilation and the standard is primarily applicable to single family houses, flats and cell offices. It can be used to determine the total outdoor air flow into a single family house or flat or, the total outdoor air flow into an individual room which has both intake and extract mechanical ventilation.

The method is based on the dilution of tracer gas (decay rate) and the continuous measurement of the tracer gas within the building. Two methods are described: in the first the tracer gas concentration is measured in every room of the house or flat; in the second the tracer gas concentration is measured in only one room in the house or flat. The first method produces the best measurement accuracy but the second requires less equipment.

The standard describes the mathematical basis of the test and lists the equipment required to perform the measurements. The preparation of the building is described and the measurement procedure presented. Data collection and analysis is considered as is the accuracy of the method. Finally a standard reporting format for the test is presented.

8.4. USA Standard ASTM E 741-83

This standard describes a technique for measuring the air change rate of buildings under natural meteorological conditions using the tracer gas dilution (decay rate) principle. Two variants of the technique are presented. In the "on site monitor" variant, tracer concentration as a function of time is measured on site directly as air samples are obtained. In the "container sample" variant, after the tracer has thoroughly mixed an initial air sample container is filled. The tracer is allowed to decay for a period of several hours during which a second and perhaps third sample container is filled. The samples can then be analyzed at a remote laboratory and air change rates can be determined from the decay in concentration.

The document describes terms specific to the standard, explains the principle of the measurements and explains the significance and use of the technique. Apparatus particular to the method is described and the measurement procedure presented. The initial data analysis and the presentation of the final results are examined. Calibration and safety procedures are considered and a standard reporting format for the test is presented. A list of suitable tracer gases is included.

9. References

After the sign # are AIRBASE numbers. If the number is between square brackets [], it relates to a book containing the quoted reference. AIRBASE numbers between brackets () relate to similar texts with a reference other than the quoted one.

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Part IV
Measurement Methods Related to Efficiency

Symbols and Units

$\underline{\mathbf{A}}$	vector containing the coefficients a, b_i, b_{ij} $(i \neq j)$ and b_{ii}	
a, b_i, b_{ij}:	coefficients in a model	
$C_r(t)$	mass concentration of a tracer at location $\underline{r}$ and time t.	[-]
$C_e(t)$	mass concentration measured in the exhaust duct	[-]
$C_o(t)$	mass concentration measured outdoors	[-]
c	equivalent volume concentrations	[-]
$\underline{\underline{C}}$	matrix of the net mass concentrations C_{ik} - C_{0k} of contaminant k in zone i.	[-]
$f(\tau)$	probability density function of the age of air particles	[s^{-1}]
$F(\tau)$	probability function of the age of air particles	[-]
M	mass of air contained in the space of interest	[kg]
m	mass of contaminant contained in the space of interest	[kg]
$\underline{\underline{M}}$	model matrix, resulting from an experimental design and a model	
$\underline{\underline{M}}$	also diagonal matrix containing the masses of air of each zone	[kg]
n	air change rate	[s^{-1}] (or [h^{-1}])
N	number of measuring points	[-]
$\underline{r}$	vector locating a point in the space	[m]
Q	fresh air flow rate (in mass terms)	[kg/s] (or [kg/h])
$\underline{\underline{Q}}$	time-averaged flow matrix	[kg/s] (or [kg/h])
q	fresh air flow rate (in volume)	[m^3/s] (or [m^3/h])
S	mass flow rate of a contaminant or a tracer	[kg/s] (or [kg/h])
$\underline{\underline{S}}$	matrix of the mass flow rates S_{ik} of tracer or contaminant k in zone i.	[kg/s] (or [kg/h])
s	volume flow rate of a contaminant or a tracer	[m^3/s] (or [m^3/h])
t	time	[s](or [h])
U	purging flow rate	[kg/s] (or [kg/h])
u	purging flow rate	[m^3/s] (or [m^3/h])
$\underline{\mathbf{V}}$	vector containing the measured quantities (v_1, v_2,...,v_n) at n locations	
v	any variable like concentration or age of air	
V	volume of the room	[m^3]
VF	variance function	
x_i	coordinates of a measured point (i = 1 to 3)	[m]
Δt	time interval	[s]
η_a	air change efficiency†	[-]
ε_a	coefficient of air change performance = 2 η_a	[-]
ε_c	local ventilation effectiveness or pollutant removal effectiveness	[-]
$\underline{\underline{\varepsilon_c}}$	matrix of ventilation effectiveness	[-]
$\langle \varepsilon_c \rangle$	room average pollutant removal effectiveness	[-]
$\underline{\underline{\varepsilon_d}}$	matrix of distribution effectiveness	[-]
$\langle \bar{\varepsilon}_d \rangle$	average distribution effectiveness	[-]
μ	relative contaminant removal effectiveness = $1/\langle \bar{\varepsilon}_d \rangle$	[-]
τ_a	air change time : $\tau_a = 2 \langle \tau \rangle$	[s]
τ_c	turn-over time of a contaminant	[s]
$\underline{\underline{\tau_c}}$	turn-over time matrix	[s]
τ_n	nominal time constant of the room	[s]
$\tau_{\underline{r}}$	local age of air at point $\underline{r}$	[s]
τ_r	mean age of air at location $\underline{r}$	[s]
$\langle \tau \rangle$	room mean age	[s]

† The word "efficiency" and the Greek letter η is reserved here for ratios having a value between 0 and 1. For other ratios, the words "effectiveness" or "coefficient of performance" and the letter ε are used.

1. Introduction

To ensure their health, safety and comfort, an efficient ventilation strategy should provide an adequate supply of fresh air to the building occupants to dilute airborne contaminants to acceptable concentrations. This efficiency can be measured at any location or for the occupied space overall, provided that the main contaminant is defined and its concentration is measurable.

Since it can be assumed that the older the air is, the greater is its contaminant concentration, knowledge of the `residence time' or `age' of air is of great importance. From these quantities, various associated expressions of efficiency or effectiveness can be calculated.

For an acceptable indoor environment, fresh air should first be distributed in the occupied space, and any contaminant generated in this space should be quickly removed. Therefore, knowledge of the flow paths of both fresh and contaminated air are also of great importance. A map of the contaminant concentrations or the ages of air may help to determine these flow paths. This map can be obtained for a particular pollutant source by measuring the concentrations at various locations within a room or, if the pollutant source is not known, by the measurement of the age of the air in the room. This map may also be estimated by computation using sophisticated codes *[Davidson and Olsson, 1987]*.

Various measurement methods, most of them using tracer gases, can be used to analyze the flow pattern and the distribution of contaminants in a room. The choice is made according to what we wish to know; examples of measurement strategies for two different requirements are given below.

To assess the **indoor air quality**

- map the contaminant concentrations resulting from several sources and a given ventilation flow pattern, or, if the main contaminant is not known,
- determine the age of the air at different locations in the room.

To assess the **room-ventilation system** itself:

- determine the air exchange efficiency, i.e. how the fresh air is distributed in the room;
- determine the ventilation effectiveness, i.e. how effective the system is in reducing room contaminant concentrations.

Each particular objective cited above in the introduction has its own measurement method(s) allowing one to measure the necessary quantities.

Definitions of the above quantities and their different measurement methods are described in the following sections.

2. Definitions

The quantities defined below are explained in greater detail elsewhere *[Sutcliffe, 1990]* and are only briefly described here.

2.1. Age of the Air

The particles of fresh air coming from outside or from the ventilation system arrive at a given location r in a room after a time τ_r which will vary from one particle to the other. τ_r is called the residence time of the particle in the room, or its age, as if it were born when entering the room. Since there is a large number of air particles, we may define a probability density that the age of particles arriving at a given location is between τ and $\tau+d\tau$ and, a probability $F(\tau_r)$ that this age is less than τ. The following relationships always hold between these two functions:

$$\frac{dF}{d\tau} = f(\tau_r) \qquad \text{and} \qquad \int_0^{\tau} f(t_r)\, dt = F(\tau_r) \tag{2.1}$$

The **local mean age of air** at a point r is defined by the average age of all the air particles arriving at that point:

$$\bar{\tau}_r = \int_0^{\infty} t f(t_r)\, dt \tag{2.2}$$

The **room mean age of air** $\langle\tau\rangle$ is defined by the average of the ages of all the air particles in the room.

2.2. Nominal Time Constant

The **nominal time constant** of a zone, is the ratio of the volume, V, to the supplied fresh air flow rate, q, (including infiltration), or the ratio of the mass of air contained in the space, M, to the mass air flow rate, Q:

$$\tau_n = \frac{V}{q} = \frac{M}{Q} = \frac{1}{n} \tag{2.3}$$

Its inverse is the specific air flow rate or air change rate, n.

The measurement methods for these parameters are the variants of the tracer decay method described in part III. These methods assume a complete mixing of the tracer. However, even in case of poor mixing, it is shown that the nominal time constant is equal to the mean age of air at the exhaust *[Sandberg, 1983]*:

$$\tau_n = \bar{\tau}_e \tag{2.4}$$

If the air leaves the zone by a single exhaust, which is likely to be the case in exhaust ventilation systems, equation 2.4, together with the methods described in Section IV.3, can be useful for the measurement of the nominal time constant or of the air change rate.

2.3. Air Exchange Efficiency

This efficiency expresses how the fresh air is distributed in the room. The time, τ_a, required on average to replace the air present in the space is given by the following expression *[Sandberg and Sjöberg, 1982]*:

$$\tau_a = 2\langle\tau\rangle \tag{2.5}$$

where $\langle\tau\rangle$ is the room mean age of air. At a given flow rate and space volume the shortest time required to replace the air within the space is given by the nominal time constant.

The air exchange efficiency†, η_a, is calculated by:

$$\eta_a = \frac{\tau_n}{2\langle\tau\rangle} \tag{2.6}$$

The air exchange efficiency is equal to one for piston-type ventilation whereas for complete mixing it is equal to 0.5. Short circuiting of air will give rise to an efficiency which is lower than 0.5.

Note that in the Standard *[ASHRAE 62-1989]*, a coefficient of air change performance, ε_a, is defined, which is twice the air exchange efficiency:

$$\varepsilon_a = \frac{\tau_n}{\langle\tau\rangle} = 2\,\eta_a \tag{2.7}$$

A complete explanation of the quantities related to air change efficiency is developed in *[Sutcliffe, 1990]*.

2.4. Ventilation Effectiveness

The ventilation or pollutant removal effectiveness expresses the efficiency in extracting the contaminants generated in the rooms, and is generally defined as the ratio of two net concentrations:

$$\varepsilon_c = \frac{C_e - C_o}{C_r - C_o} \tag{2.8}$$

where

C_e is the contaminant concentration in the exhaust air,

C_o is the contaminant concentration in the outdoor air, and

C_r is the contaminant concentration at the location of interest, r.

† See note under "Symbols and Units"

The location of interest can be:

- any particular location $\underline{r}$, the result being $\varepsilon_c(\underline{r})$
- the location with the highest contaminant concentration, which gives the lowest ventilation effectiveness, $\varepsilon_{c,min}$
- all the space, by taking the average concentration $\langle C_r \rangle$ over the space. The result will then be the average ventilation effectiveness, $\langle \varepsilon_c \rangle$

The ventilation effectiveness is zero if there is a short cut between exhaust and inlet grilles ($C_e = C_o$), it is equal to one for complete mixing ($C_e = C_r$) and is infinity at the locations reached by pure fresh air ($C_r = C_o$).

It must be pointed out that the definition and the measurement of ε_c specifies in most cases the measurement of the exhaust concentration C_e. This, in turn, requires the air to leave the room through a single exhaust duct. The definition can be adapted to accommodate multiple exhaust ducts if the flow rates through all of them are measured.

A complete explanation of the quantities related to pollutant removal effectiveness is developed in *[Brouns, 1991]*.

2.5. Age of a Contaminant

The concept of the age of air can be easily adapted to any contaminant or to any tracer simulating a contaminant. This contaminant is assumed to be 'born' when entering the room and its age is the time period spent in the space since this event.

Thus the equations of Section 2.1 can be used, defining the age of a contaminant, τ_c, the mean age at location $\underline{r}$, $\tau_c(\underline{r})$, and the room mean age of a contaminant, $\langle \tau_c \rangle$.

2.6. Turn-over Time of a Contaminant

If the contaminant is injected at a steady flow rate, S, in a room ventilated with an air flow rate, Q, an equilibrium will be reached after a while. The room will then contain a mass, m, or a volume, v, of contaminant. The turn-over time, τ_c, is defined similarly to the nominal time constant:

$$\tau_c = \frac{v}{s} = \frac{m}{S} \tag{2.9}$$

2.7. Purging Flow Rate

The purging flow rate is the mass flow rate, U, or the volume flow rate, u, at which the contaminant is eliminated:

$$U = \frac{S}{C} \qquad \text{and} \qquad u = \frac{s}{c} \tag{2.10}$$

Depending on the location where the concentration is measured, this flow rate can be estimated instantaneously and locally, or averaged over the space of interest:

$$\langle U \rangle = \frac{S}{\langle C \rangle} \qquad \text{and} \qquad \langle u \rangle = \frac{s}{\langle c \rangle} \tag{2.11}$$

or over time, giving $\bar{U}$

2.8. Relationships Between Ways of Expressing the Effectiveness.

It is shown that the average ventilation effectiveness is also the ratio of the nominal time constant to the contaminant turn-over time *[Sandberg, 1983]*:

$$\langle \varepsilon_c \rangle = \frac{\tau_n}{\tau_c} \tag{2.12}$$

Using the definitions of τ_n and τ_c:

$$\langle \varepsilon_c \rangle = \frac{M}{Q}\frac{S}{m} = \frac{\langle U \rangle}{Q} \tag{2.13}$$

since, by definition, $\langle C \rangle = m/M$. So the average ventilation effectiveness is also the ratio of the room average purging flow rate to the fresh air flow rate. In other words, the average purging flow rate could be named as the 'effective' flow rate, since:

$$\langle U \rangle = \langle \varepsilon_c \rangle Q \tag{2.14}$$

This denomination is however not recommended, since there are other definitions of 'effective' flow rates in the literature. For example, *[Sherman, 1986]* defined an average effective flow rate which results in the same time average tracer or contaminant concentration as the measured time average concentration:

$$\bar{Q}_{eff} = \frac{\bar{S}}{\bar{C}} \tag{2.15}$$

Since the average of a ratio is not the ratio of the averages, this time averaged quantity is not equal to the average purging flow rate.

2.9. Multizone point of view

There are several ways to address the efficiency in changing the air or in removing the contaminants in multizone buildings. First, any variable which depends on the location as the mean age of air or local effectiveness can be used as it is in multizone buildings.

It is however convenient to present either more systematic or simpler ways in expressing these concepts mathematically.

The **τ-matrix** presented in Section III.2.5.2 is the multizone equivalent of the nominal time constant. Following *[Sherman, 1989]*, a multizone **turn-over time matrix**, $\underline{\tau}_c$, can be defined:

$$\underline{\tau}_c = \underline{\underline{M}}\,\underline{\underline{C}}\,\underline{\underline{S}}^{-1} \tag{2.16}$$

Where:

$\underline{\underline{M}}$ is a diagonal matrix containing the masses of air of each zone

$\underline{\underline{C}}$ matrix of the net mass concentrations C_{ik} - C_{0k} of contaminant k in zone i. $\underline{\underline{M}}\,\underline{\underline{C}}$ is the matrix containing the masses of contaminant k in zone i.

$\underline{\underline{S}}$ matrix of the mass flow rates S_{ik} of contaminant k in zone i.

Each element τ_{ik} of the $\underline{\tau}_c$ matrix is hence the turn-over time of the contaminant k in zone i.

The matrix of ventilation effectiveness, $\underline{\varepsilon}_c$, can similarly be defined as:

$$\underline{\varepsilon}_c = \underline{\tau}\,\underline{\tau}_c^{-1} \tag{2.17}$$

An **overall effectiveness**, averaged over time and zones can then be the weighted average of the elements of this matrix:

$$\langle \bar{\varepsilon}_c \rangle = \frac{\Sigma\, \bar{\underline{\varepsilon}}_c\, \bar{\underline{Q}}}{\Sigma\, \bar{\underline{Q}}} \tag{2.18}$$

were $\bar{\underline{Q}}$ is the time-averaged flow matrix and the sum is over all the elements of each matrix.

A concept which relates the concentration in a location or a zone to the hypothetical concentration, C^*, which could be reached in the building considered as a single, well mixed zone, is crucial in determining how concentrations from a single source is distributed in a building. A **distribution effectiveness** can be defined as a matrix *[Sherman, 1989]*:

$$\underline{\varepsilon}_d = \frac{1}{C^*}\,\underline{\underline{C}} \tag{2.19}$$

Since the local concentration may be smaller or larger than the "well mixed" concentration, the matrix $\underline{\varepsilon}_c$ contains elements which can be larger or smaller than one. A global average gives:

$$\langle \bar{\varepsilon}_d \rangle = \frac{\langle \bar{C} \rangle}{\bar{\bar{C}}^*} \tag{2.20}$$

[Haghighat, Fazio and Rao, 1990] defined a **relative contaminant removal effectiveness**, μ, which is the inverse of $\langle \varepsilon_d \rangle$. If the average is taken over the whole building or if equation (2.20) is used in a single zone, $\langle \varepsilon_d \rangle$ is related to other quantities defined above:

$$\langle \bar{\varepsilon}_d \rangle = \frac{2\eta_a}{\langle \varepsilon \rangle} = \frac{\tau_c}{\langle \tau \rangle} \tag{2.21}$$

The measurement of these quantities defined for multizone buildings involves the measurement of the following quantities:

For the **turn-over time matrix**, the net mass concentrations $C_{ik} - C_{0k}$ and the mass flow rates S_{ik} of contaminant k in zone i as well as the volumes and densities of air in each zone should be measured.

The matrix of **ventilation effectiveness**, $\underline{\underline{\varepsilon}}_c$, can be deduced from the above measurement and from the τ-matrix, using equation (2.17). Measurement techniques for the τ-matrix are found in part III. The overall efectiveness is deduced from this matrix, by averaging over time and zones.

The matrix of **distribution effectiveness**, $\underline{\underline{\varepsilon}}_d$, requires measurements of the concentrations of the contaminant of interest in each zone, of the total strength of source(s) spreading that contaminant in the building, of the volumes and of the densities of air in each zone.

The **relative contaminant removal effectiveness** or the average distribution effectiveness are directly deduced from the results of the measurements mentionned above, using eluqtion (2.20).

3. Local Age of Air

It has been shown that the probability functions (2.1) can be measured by recording the time history of the tracer concentration, $C_r(t)$, at any point, r, by either of three strategies as follows *[Sandberg and Sjöberg, 1982], [Sutcliffe, 1990]*:

- uniform concentration of tracer is achieved at the beginning of the test
- the tracer is injected at a constant rate throughout the test
- a short pulse of tracer is released at the air inlet (assumes single inlet).

The concentration histories are measured by analyzing air samples taken at time intervals, Δt, at the locations of interest. To minimize the discretization errors, this time interval should be small compared to the nominal time constant of the room. A recommended value is:

$$\Delta t \leq 0.2\, t_n \tag{3.1}$$

The mean age of air at a given location in the room can be deduced from the age distributions represented by the concentration histories. It is necessary for the experiment to proceed for a time period larger than the nominal time constant of the room, that is about 1.5 τ_n. The tracer concentration in the supply air should also be measured.

3.1. Pulse and Step-up Methods

These methods can be used in mechanically ventilated rooms where all the fresh air is brought through a single air inlet duct. The the room air is analyzed before injection to give the initial concentration C_0.

At time t_0, a suitable tracer gas (see III 5.6) is injected into the inlet duct, either as a short pulse, over a time period much less than the measurement interval Δt, or at a constant flow rate. The quantity of tracer injected or the tracer flow rate depends on the air change rate and on the maximum required concentration as shown:

$$\text{Pulsed injection: } \textit{Injected volume} \approx V\, C_{max} \tag{3.2}$$

$$\text{Constant flow rate: } \textit{Injected flow rate} \approx n\, V\, C_{max} \tag{3.3}$$

To ensure good mixing of the tracer in the air entering the room, the tracer should be injected at a point in the duct upstream of the inlet grille, whilst sufficiently near to avoid losses through interconnecting sections and to minimize losses through the duct walls. When using the pulse technique, the test proceeds until the tracer concentration has fallen to zero (or to the background concentration) at all measurement locations. Constant injection, however, should proceed until a steady concentration is observed at all measurement locations. The interpretation of the concentration histories is summarized below (section 3.3).

3.2. Decay Method

This procedure can be used for any space in which an initial uniform distribution of tracer can be achieved, by whatever means. This includes both naturally ventilated and mechanically ventilated spaces with either single or multiple supply or exhaust ducts, in any combination.

A suitable tracer is dispersed throughout the space with the aid of fans or paddles to obtain a uniform measurable initial concentration C_{r0}. Injection is stopped at time t_0 and the concentration continues to be recorded as it falls at all measurement locations, either to zero (or background) or until exponential decay is achieved at all locations.

In some cases it may be that the initial disturbance of the air flow pattern caused by artificial mixing may persist for a significant part of the test. One possible method to overcome this is to use a microprocessor-controlled system [e.g. a CCTG instrument, see III.6.3] designed to achieve and maintain a constant concentration at multiple locations.

3.3. Interpretation of Results

First, the background (or supply) concentration is subtracted from all measurements, and time should begin from zero start of the test (i.e. elapsed time) by subtracting from all time values. The local mean age at a given measurement location is obtained by evaluating the expressions shown in Table 3.1, and involve numerical integration of the concentration histories.

Method for injection	Distribution at location r	Local mean age of air $\bar{\tau}_r$
Pulsed injection in inlet duct	$f(\tau) = \dfrac{C_r(\tau)}{\int_0^\infty C(t)\,dt}$	$\dfrac{\int_0^\infty t\,C_r(t)\,dt}{\int_0^\infty C_r(t)\,dt}$
Step injection in inlet duct	$F(\tau) = \dfrac{C_r(\tau)}{C_r(\infty)}$	$\int_0^\infty (1 - \dfrac{C_r(t)}{C_r(\infty)})\,dt$
Decay after uniform concentration within the room	$F(\tau) = \dfrac{C_r(\tau)}{C_r(0)}$	$\dfrac{\int_0^\infty C_r(t)\,dt}{C_r(0)}$

Table 3.1: Equations giving the probability functions for the age of air and the mean age of air using different measuring strategies. The first two techniques can be used only if there is a single air inlet.

These integrals are taken from 0 to infinity, where 0 corresponds to the time t_0. Since the measurement is performed over a finite time period, there remains a residual part to be estimated. This estimate can be obtained by assuming that by the end of the measurement, the concentration follows an exponential curve (fig. 3.1 and 3.2).

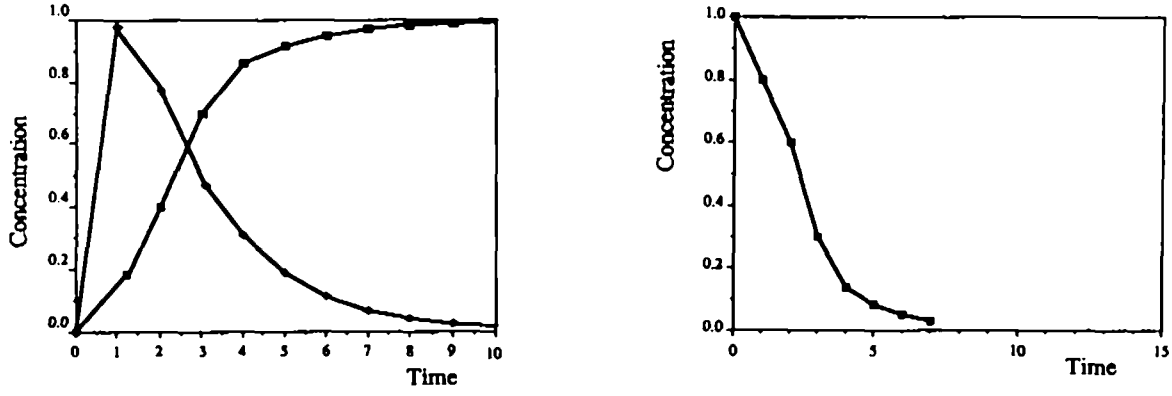

Figure 3.1: Concentration versus time for an age of air measurement using the pulse and the constant injection method (left) or the decay method (right).

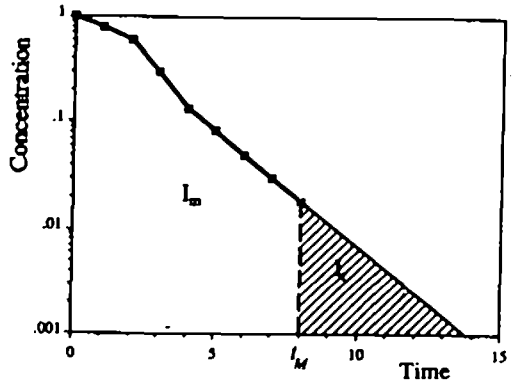

Figure 3.2: Logarithms of the concentrations for the decay method, showing the two parts for the integration.

The integral is decomposed in two parts: the measured part I_M and the residual part I_R:

$$\int_0^{\infty} f(t)\,dt = \int_0^{t_M} f(t)\,dt + \int_{t_M}^{\infty} f(t)\,dt \qquad (3.4)$$

$$I = I_M + I_R$$

The integrand, $f(t)$ is either the concentration or the concentration multiplied by the time.

I_M can be integrated by any numerical method; using the trapezium method, for example, if there are M records of the values of the function $f(t)$, then:

$$I_M = \sum_0^{M-1} \frac{(f(t_i) + f(t_{i+1})}{2} \qquad (3.5)$$

The residual integral is obtained the following way, assuming that, from time t_M on:

$$C_r(\tau) = C_r(t_M) \exp(-t/\tau) \qquad (3.6)$$

The time constant τ is obtained using the last N measurements, for which a logarithmic plot shows an exponential decay. τ can be deduced from two measurement points:

$$\tau = \frac{t_M - t_{M-N}}{\ln(C_r(t_{M-N})) - \ln(C_r(t_M))} \qquad (3.7)$$

or from the last N measurement points using the least square fit method (see Appendix 3).

If f(t) is the concentration $C_r(\tau)$, then:

$$I_R = \tau\, C_r(t_M) \qquad (3.8)$$

If f(t) is the concentration multiplied by the time, $t\, C_r(\tau)$, then:

$$I_R = \tau\, C_r(t_M)\,(t_M + \tau) \qquad (3.9)$$

3.4. Possible Errors and Choice of the Injection Method

A real experiment and a simulation using the three methods presented above were performed with the objective of determining which methods is less sensitive to measurement errors *[Sutcliffe and Waters, 1990]*.

It was found that the decay method may be slightly more accurate than the two other methods and is the easiest to use from a practical point of view. The step-up method can give rise to large errors, due to uncertainties in the values of the steady state concentration, C_∞. These errors can be specially important in the measurement of room mean age (see Section IV.5).

There are also mixing problems, which differ with the method. the step-up method requires the injection of a relatively large amount of tracer gas in a short pulse in the inlet duct, and this quantity might be difficult to mix to the fresh air. On the other hand, the decay method requires a good initial mixing, which can be obtained by the use of mixing fans. This mixing, however, disturbs the natural flow pattern and might change the distribution of the age of the air in the room..

3.5. Measurement of the Local Mean Age of a Contaminant

The procedures are exactly the same, except that the contaminant, or a tracer simulating the contaminant, is released at any relevant location in the space, that is where the contaminant source is located.

The concentration of some contaminants, as water vapor, carbon gas, radon, can be easily measured at the levels usually encountered in buildings, but some others like body odors, some solvents, etc, are difficult to quantify in terms of concentration.

On the other hand, one might be interested in a contaminant which is common but which comes from a specific source. For example, the water vapor or carbon gas coming from a gas cooker are impossible (or at least difficult) to differentiate from the same contaminants coming from other sources. In these cases, it is of great interest to simulate the contaminant with another, more practical

gas, used as tracer.

The advantage of tracers simulating the contaminants is that they are less toxic, easily measurable in small quantities, and their source strength can be easily assessed.

The choice of the simulating tracer is nevertheless of importance when buoyancy effects are expected. In this case, the tracer should have a density close to the density of the simulated contaminant. Since, for gases dissolved in air at temperatures over their dew point, the density is proportional to the molecular weight, it may be easier to chose the tracer which presents the same molecular weight as that of the contaminant. The Table III.5.13 gives indications on these values for most of the gases used as tracers.

4. Planning of Mapping Experiments

Mapping either the contaminant concentration or the age of air in a room can be of great advantage in studying the contaminant or air flow pattern and their effects on occupants. Such maps have already been calculated using computer codes *[Davidson and Olsson, 1987]* and some qualitative representations have been drawn from measurements *[Valton, 1989]*.

The purpose of this chapter is to propose a systematic way to obtain a preliminary map of contaminant concentration or of the age of air from measurements in a room. Such a map allows one to locate the dangerous locations or the dead zones within the measured room, under the conditions prevailing during the experiments.

4.1. Minimum number of measurements

A map of any scalar variable v in a three-dimensional room is basically obtained by measuring the variable at each node of a network and interpolating between these nodes. Such measurements are however very expensive and may be unfeasible; if only 5 values are taken on each axis, at least 125 measurements are required. Therefore, it makes sense to look for methods needing a minimum number of measurements points.

The minimum number of measurements depends on the objective of the mapping experiment, or more precisely on the empirical model which is chosen to represent the map of the variable v.

Any infinitely derivable function (as v is assumed to be) can be developed in a Taylor series around a given point. This gives a polynomial which can be approximated by its k+1 first terms, k being the degree of the polynomial. In the following, models of degree 1 and 2 will be considered.

If a **linear** model is adopted (degree 1) , such as:

$$v = a + \Sigma_i b_i x_i \tag{4.1}$$

where x_i are the three coordinates of the measured point, only 4 measurements are needed to obtain a set of coefficients $\{a, b_i\}$. If more measurements are made, the coefficients may be obtained by a least square fit procedure provided there is no (or negligible) uncertainty on the coordinates. If their coordinates differ for the other points, these supplementary measurement points give information on the validity of the used model.

If the linear model does not appear to be valid, more sophisticated models may be used. For example, a **quadratic** model:

$$v = a + \Sigma_i b_i x_i + \Sigma_{i \neq j} b_{ij} x_i x_j + \Sigma_i b_{ii} x_i^2 \tag{4.2}$$

which contains 10 coefficients, can be chosen. Such a model may already fit many practical situations and present minimal and maximal value(s). To determine its coefficients, measurements at 10 locations is the minimum.

An intermediate model is the **interactions** model:

$$v = a + \Sigma_i b_i x_i + \Sigma_{i \neq j} b_{ij} x_i x_j \tag{4.3}$$

for which 7 coefficients must be determined. Table 4.2 summarizes the minimum number of measurements needed.

Model	Linear	Interaction	Quadratic	Cubic	4th degree
Dimensions					
2	3	4	6	10	15
3	4	7	10	20	35

***Table 4.2:** Minimum number of measurements needed to obtain the coefficients of a k^{th} degree polynomial empirical model representing a variable in a 2 and 3-dimensional space.*

4.2. Location of the Measurement Points

The next problem is, where should we locate the measurement points? There are numerous possible experimental designs, but they do not give the expected results with the same accuracy. For example, it is obvious that, to fit a linear model of one dimension only ($y = ax + b$), the location of the two

measurement points (the minimum number) which gives the best accuracy on a and b is at the ends of the experimental domain. If the model is more sophisticated or is for a larger number of dimensions, the choice is not so obvious. However, several tools exist for planning such experiments, which may be found in the literature *[Feneuille, Mathieu and Phan-Tan-Luu, 1983], [Bandemer and Bellmann, 1979], [Fedorov, 1972]* and are applied below.

However, since points close to the walls do not represent the inner volume, the sampling points should not be located near the walls or in the corners of the room. In the followings, the "room" or the "experimental domain" is a volume which is smaller than the actual measured space by about 20% in each direction.

Let us take a coordinate system in such a rectangular volume using as the unit, for each direction, the half-length of that domain in that direction. Any point in the "room" is then located by three numbers included in the interval [-1, +1].

The experimental design can be represented by a rectangular matrix with 3 columns (one for each coordinate) and as many lines as measurement points. For example the design:

Point	x	y	z
1	1	1	1
2	-1	-1	-1
3	1	-1	1
4	-1	1	-1

is a two-level factorial design and is very well suited to obtain the coefficients of a linear model.

A general condition is that, to obtain the coefficients of a polynomial of degree k, each of the variables x, y and z shall take at least $k+1$ values in the experimental design, which should have at least $k+1$ levels on each axis.

To establish the most efficient design, the several criteria described can be used.

4.3. Criteria for Location of the Measurement Points

4.3.1. The Model Matrix $\underline{\underline{M}}$

First, let us look at the method used to obtain these coefficients. For each point, the model is applied, replacing the x_i by their values given by the experimental design. A system of equations (one equation for each location) is obtained this way, which can be written in a matrix notation:

$$\underline{V} = \underline{\underline{M}}\,\mathbf{A} \tag{4.4}$$

where:

$\underline{V}$ $(v_1, v_2, \ldots, v_n)$ is a vector containing the measured quantities at the n locations,

$\underline{\underline{M}}$ is a matrix, each line of which corresponding to one location. Its first column is filled with ones and correspond to a constant in the model. The next 3 columns may contain the coordinates of the locations if the model contains linear terms. The next 3 columns may contain the products of these coordinates two by two (e.g. x_1x_2, x_1x_3, x_2x_3) in case of interaction terms and, for a quadratic model, the next three columns contain the squares of the coordinates. Other models will produce other matrices.

$\mathbf{A}$ is a vector containing the coefficients (e.g. a, b_i, b_{ij} $(i \neq j)$ and b_{ii}) of the model.

In the general case, $\underline{\underline{M}}$ is rectangular and the least square fit procedure is used:

$$\mathbf{A} = (\underline{\underline{M}}'\underline{\underline{M}})^{-1}\,\underline{\underline{M}}'\,\underline{V} \tag{4.5}$$

where $\underline{\underline{M}}'$ is the transposed matrix of $\underline{\underline{M}}$. This equation is also valid if M is a square matrix, but reduces to the simpler equation:

$$\mathbf{A} = \underline{\underline{M}}^{-1}\,\underline{V} \tag{4.6}$$

In any case, a matrix should be inverted and the determinant of this matrix should not be zero! Since this determinant can be calculated before making the measurements, it is a first criterion for the choice of the experimental design.

4.3.2. Variance of the Calculated Response

If the coefficients are known, an estimate v_e of the value of the variable v can be obtained at each location in the enclosure:

$$v_e = \underline{A}' \underline{t} \tag{4.7}$$

where $\underline{t}$ is the vector $(1, x_1, x_2, x_3)$

If σ^2 is the experimental variance of the measured variable v, the variance $\sigma^2(v_e)$ of the estimated variable is:

$$\sigma^2(v_e) = \underline{t}' (\underline{\underline{M}}'\underline{\underline{M}})^{-1} \underline{t}\, \sigma^2 \tag{4.8}$$

A variance function can be defined:

$$VF = \frac{N}{\sigma^2} \sigma^2(v_e) = N \underline{t}' (\underline{\underline{M}}'\underline{\underline{M}})^{-1} \underline{t} \tag{4.9}$$

where N is the number of measurements. VF depends on the experimental design ($\underline{\underline{M}}$ and N) and on the location $\underline{t}$ and can hence be calculated before doing any measurement.

If VF depends only on the distance to the origin (or the module of $\underline{t}$), the experimental design is said to be **isovariant by rotation**. If VF is a constant within the experimental domain, the design gives a **uniform accuracy**. A good experimental design should have a small variance function, which is as constant as possible.

If $(\underline{\underline{M}}'\underline{\underline{M}})^{-1}$ is diagonal, the design is **orthogonal**. In this case, the variance function is minimum.

4.3.3. Condition of the Model Matrix

As it is presented in appendix 2, section 3.5, the condition number of the matrix $\underline{\underline{M}}$ plays an important role on the upper bound of the relative errors on the result.

This condition multiplies the experimental errors and transmits these errors into the result $\underline{A}$. This number depends on the experimental design and on the chosen model but does not depend on the results of the measurements. Hence it can be calculated **before** doing any measurement and constitutes one more criterion, which is relatively easy to compute, for the choice of the experimental design. This is a much better criterion than the determinant of $\underline{\underline{M}}'\underline{\underline{M}}$.

4.3.4. Expendability of the Experimental Design

It may be interesting that the measurements performed to obtain the coefficients of a first degree polynomial are not lost and could be used with other measurements to expand the polynomial to a higher degree. Some designs are expandable that way, some others are not.

4.4. Examples of experimental designs

Several experimental designs were examined with the aim to map a rectangular volume or a rectangular area *[Roulet, Compagnon, Jakob, 1990]*. The tested models were the linear, the interaction and the quadratic models. Several of these designs were found to be unusable (singular matrix or too large a condition number for the quadratic model). Some useable examples are given below.

In practice, the experimental domain is a little bit smaller than the measured space, since it is seldom useful to have measurements of contaminant concentration or of age of air very near the walls, ceiling or floor. Therefore, the measured volume is about 20% smaller in each dimension, the samples of air not being taken nearer the wall than 0.1 times the characteristic enclosure dimension.

4.4.1. Factorial designs

A k-dimensional, l-level factorial design is obtained by dividing the experimental domain (e.g. the interval [-1, 1]) on each axis into l equidistant levels. The complete factorial design contains all the points obtained by the l^k combination of the l possible values of the k coordinates.

The number of points in a full factorial design is l^k. If l and k are greater than 2, the full factorial designs often have many more points than the minimum required, and are therefore rarely used. However, partial factorial designs can be obtained by selecting the required number of measurement points from the full design. Some examples are given below.

4.4.2. 2-dimensional designs

The 2-D, 2 level full factorial design:

No	x	y
1	-1	-1
2	1	-1
3	-1	1
4	1	1

is well suited for a linear model. This orthogonal design allows one to obtain the coefficients of that model with the best accuracy and is isovariant by rotation. If, for economical reasons, one point is omitted, the condition number doubles, that is the inaccuracy of the coefficients is twice that based on 4 measurement points.

Adding a 5th point at the center (0,0) allows one to obtain the coefficient of the interaction term b_{12}, without loss of accuracy.

The following two points:

No	x	y
6	-1	0
7	1	0

can be added to obtain a minimum design for a quadratic model, which has a condition number of 6.3.

The 2-D full factorial design with three levels:

No	x	y
1	-1	-1
2	0	-1
3	1	-1
4	-1	0
5	0	0
6	1	0
7	-1	1
8	0	1
9	1	1

has a condition number of 4.4 for a quadratic model.

4.4.3. 3-dimensional designs

In three dimensions, the four point design:

No	x	y	z
1	-1	-1	1
2	1	-1	-1
3	-1	1	-1
4	1	1	1

is perfect for a linear model. It can be expanded to a full factorial design:

No	x	y	z
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1

which is good when used with interaction model. Adding 6 points on both ends of the axes, and a center point, that is the centered star design:

No	x	y	z
9	1	0	0
10	0	1	0
11	0	0	1
12	-1	0	0
13	0	-1	0
14	0	0	-1
15	0	0	0

gives a so-called composite centered design, suitable for a quadratic model, having a condition number for $\underline{\underline{M}}'\underline{\underline{M}}$ of 4.4. If fewer points are wanted, the points 8, 5 and 2 can be deleted (in that order) giving finally a design having 12 points and a condition number of 4.8. Finally, deleting two more points (3 and 15) gives the design C3, which has 6 points in the center of the faces and 4 points at opposite corners (fig. 4.1).

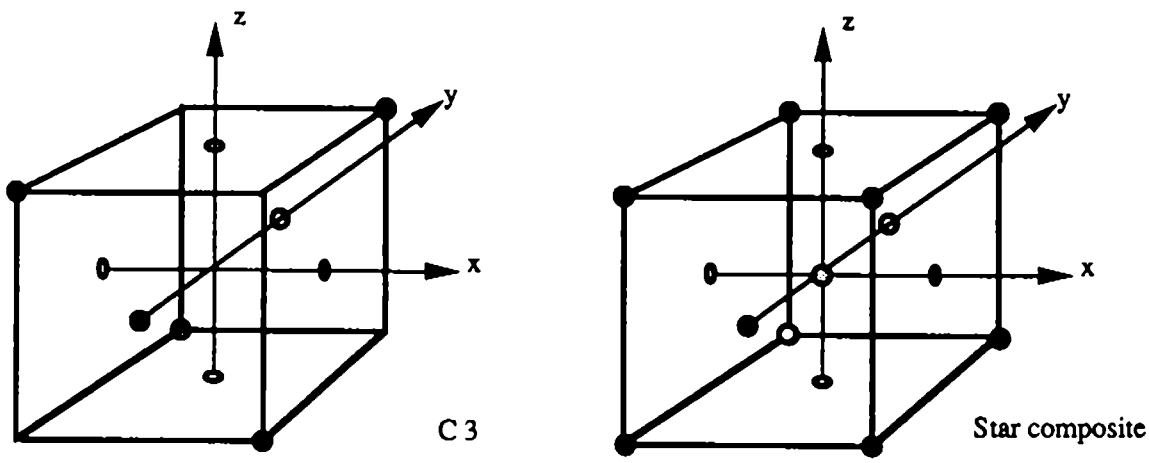

Figure 4.1: Experimental designs C3 (left) and composite centered (right)

The condition number of $\underline{\underline{M}}'\underline{\underline{M}}$ calculated using the absolute value norm $\|\underline{\underline{M}}'\underline{\underline{M}}\|_1$ (see appendix 2.4) for these designs and three models are given in table 4.3.

Experimental design	Number of points	Quadratic model	Interactions model	Linear model
2-dimensional designs				
2-level part factorial	3	-	-	2.0
2-level full factorial	4	-	-	1.0
Centered 2-level fact.	5	-	1.0	1.0
Minimum for quadratic	6	6.3	1.0	1.0
3-level full factorial	9	4.4	1.0	1.0
3-dimensional designs				
2-level half factorial	4	-	-	1.0
2 level full factorial	8	-	1.0	1.0
C 3	10	4.3	3.2	1.0
Composite centered	15	4.4	1.0	1.0

Table 4.3: Condition number of $\underline{\underline{M}}'\underline{\underline{M}}$ for some experimental designs and three models. No figure indicates that this design cannot be used with the corresponding model (not enough experiments).

There are numerous other possibilities which can be imagined or found in the literature *[Feneuille, Mathieu and Phan-Tan-Luu, 1983], [Bandemer and Bellmann, 1979], [Fedorov, 1972]*. If such a design is planned to be used, it is advisable to compute first the condition number of $\underline{\underline{M}}'\underline{\underline{M}}$ and/or values of the variance function at several locations in the room

5. Room Mean Age of Air and Air Exchange Efficiency

5.1. Measurement in the Exhaust Duct

The average of the local mean age of air over the whole room is the room mean age of air $\langle\tau\rangle$. If the air leaves the room through a single opening or duct, this room mean age can be also measured with tracer gas, the methods of injection being the same as in Chapter IV.3 but the concentration $C_e(t)$ being measured in the exhaust duct *[Sandberg, 1984]*. Table 5.2 gives the appropriate formulae and the discrete integration method is already presented in Section IV.3.3.

Method for injection	Room mean age of air $\langle\tau\rangle$
Pulsed injection in inlet duct	$\frac{1}{2}\,\frac{\int_0^\infty t^2 C_e(t)\,dt}{\int_0^\infty t\,C_e(t)\,dt} = \frac{q}{2V}\,\frac{\int_0^\infty t^2 C_e(t)\,dt}{\int_0^\infty C_e(t)\,dt}$
Step injection in inlet duct	$\frac{\int_0^\infty t\,(C_e(\infty) - C_e(t))\,dt}{\int_0^\infty (C_e(\infty) - C_e(t))\,dt} = \frac{q}{V}\int_0^\infty t\left(1 - \frac{C_e(t)}{C_e(\infty)}\right)dt$
Decay after uniform concentration within the room	$\frac{\int_0^\infty t\,C_e(t)\,dt}{\int_0^\infty C_e(t)\,dt} = \frac{q}{V}\int_0^\infty t\,\frac{C_e(t)}{C_e(0)}\,dt$

Table 5.2: Equations to obtain the room average age of air from the record of the concentration $C_e(t)$ of a tracer in the exhaust duct using different measuring strategies. Note that q/V is the room air change rate or the inverse of the nominal time constant.

5.2. Measurement in the Room

If, as it is often the case, the air leaves the room through multiple openings, leaks and outlets, the technique mentioned above cannot be used. However, the local age of air $\tau(\underline{r})$ can be measured and mapped as well as a concentration, using the same experimental design.

The room mean age may then be calculated in either of two ways:

a) averaging directly the measurements of the local mean ages:

$$\langle\tau\rangle = \frac{1}{N}\sum_i \tau_i(\underline{r}_i) \tag{5.1}$$

b) using a model to interpret the measurements and average the obtained map. If a linear or interaction model is used, the room mean age of air is simply the constant term of the model. If a quadratic model is used (like equation 4.2), then:

$$\langle\tau\rangle = a + \frac{2}{3}\sum_i b_{ii} \tag{5.2}$$

where a is the constant term of the model and b_{ii} are the coefficients of the square terms.

Finally, if a full flow matrix is measured using multizone tracer techniques (see part III), the room mean ages can be deduced from this flow matrix as explained in section III 2.5 *[Roulet, Compagnon, Jakob, 1990]*.

5.3. Measurement of the Air Exchange Efficiency

The **air exchange efficiency** η_a defined in equation (2.5) can be derived from the following measurements: the air change rate (or the fresh air flow rate q provided to the room and the volume V of the room) and the room mean age of air $\langle\tau\rangle$.

The air flow rate, q, can be measured by the methods described in Part III. If there is a mechanical ventilation system, the methods described in Part V may also be used, provided that the flow rate measured in the duct is equal to the outdoor air flow rate. This is the case in balanced ventilation systems provided that they are correctly designed and constructed, so that the infiltration rate is negligible and that there is no recirculation or short circuit between inlet and exhaust ducts. In exhaust fan systems, q may be approximately determined by measuring the air flow rate in the exhaust duct(s), as long as there are no leaks upstream the measured section.

Note that the room mean age of air is deduced from the air exchange efficiency if the rightmost relations of table 6.2 are used. The measurements at the exhaust duct can therefore provide directly the air exchange efficiency. Table 5.3 gives the derived equations.

Method for injection	Air exchange efficiency η_a
Pulsed injection in inlet duct	$\dfrac{\int_0^\infty C_e(t)\,dt}{\int_0^\infty t^2\,C_e(t)\,dt}$
Step injection in inlet duct	$\dfrac{1}{2\int_0^\infty t\left(1-\dfrac{C_e(t)}{C_e(\infty)}\right)dt}$
Decay after uniform concentration within the room	$\dfrac{1}{2\int_0^\infty t\,\dfrac{C_e(t)}{C_e(0)}\,dt}$

Table 5.3: Equations to obtain the air exchange efficiency from the record of the concentration $C_e(t)$ of a tracer in the exhaust duct using different measuring strategies.

5.4. Choice of the injection method

Since the step-up method requires a long time period to reach the steady state, during which the air flow pattern may change, it is not recommended for the measurement of the room mean age. Both pulse and decay methods give reliable results when used adequately *[Niemela, Saamanen, Koskela, 1989]*. This is confirmed by a more recent experimental and numerical study *[Sutcliffe and Waters, 1990]* (see Section IV.3.5).

Note that the step-up method requires the injection of a large amount of tracer gas in a short pulse in the inlet duct, which might be difficult to mix to the fresh air, while the decay method requires a good initial mixing, which may disturb the natural flow pattern.

6. Measurement Methods Related to Ventilation Effectiveness

6.1. Ventilation Effectiveness

The ventilation effectiveness, ε_c, defined in equation (2.6) can be obtained by measuring the three concentrations: C_e in the exhaust air, C_o in the outdoor air and C_x at the location of interest.

It must be pointed out that, the definition and the measurement of ε_c needs the measurement of the exhaust concentration, C_e. That means that the air leaves the room through a single exhaust duct.

However, if the contaminant source strength, S_c, and the exhaust air flow rates, Q_e, are known or measured, equation (2.5) together with the equation of mass conservation lead to:

$$\varepsilon_c = \frac{S_c}{Q_e (C_r - C_o)} \tag{6.1}$$

Equation (6.1) allows one to measure the ventilation efficiency by simulating the pollutant sources with a tracer gas injected at constant rate at the location(s) of the pollutant sources, and measuring the resultant tracer concentrations, C_r, at the location of interest.

Depending on the purpose of the measurement, C_r can be:

- a given, interesting location (for example at the nose of an occupant). The local ventilation effectiveness, $\varepsilon_c(\underline{r})$, is then obtained. By locating several measurement points, $\underline{r}$, according a proper experimental design, a map of the efficiency may be drawn.
- the location of the maximum concentration in order to obtain the lower limit of ε_c.
- a map of the efficiency may be drawn from measurements at several points based upon a proper experimental design. From this map, the location of the minimum efficiency and the average efficiency, $\langle \varepsilon_c \rangle$, can be determined.

The nominal time constant, τ_n, is equal to the mean age of air at the exhaust, $\bar{\tau}_e$, and the turn-over time of a contaminant, τ_c, equals the mean age of that contaminant at the exhaust, τ_{ce}. Hence, using equation (2.12), the average ventilation effectiveness, $\langle \varepsilon_c \rangle$, can be obtained from the measurement of $\bar{\tau}_e$ and τ_{ce}:

$$\langle \varepsilon_c \rangle = \frac{\bar{\tau}_e}{\tau_{ce}} \tag{6.2}$$

6.2. Multizone Measurement Methods

6.2.1. Multizone Ventilation Effectiveness

The other quantities defined in Section IV.2 are obtained using their definitions or the relation presented in the same section. For example, the multizone efficiency matrix can be obtained by the following procedure:

- using a multizone method, the flow matrix, $\underline{\underline{Q}}$, is measured as well as the air mass matrix, $\underline{\underline{M}}$. From these, the τ-matrix is obtained by (see Section III.2.5.2):

$$\underline{\underline{\tau}} = \underline{\underline{Q}}^{-1} \underline{\underline{M}} \tag{6.3}$$

- the source strength, $\underline{S}$, and the room concentrations, $\underline{C}$, of either the contaminants of interest or the tracers simulating them are measured, the sources being located according the purpose of the test;
- equation (2.16) allows one to calculate the turn-over time matrix, $\underline{\underline{\tau}}_c$, and equation (2.17) is used to obtain the matrix of ventilation effectiveness.
- the overall effectiveness can be deduced using equation (2.18).

6.2.2. Distribution effectiveness, and relative contaminant removal effectiveness

These quantities could be directly obtained from the equations (2.21), if both ventilation efficiency and effectiveness or the contaminant turn-over time and the average age of air are known. These quantities, however, require measurement of the contaminant concentration in the exhaust duct. If this duct is not available (either natural ventilation or too many exhaust ducts), they cannot be directly

measured and equation (2.20) can be used *[Haghighat, Fazio and Rao, 1990]*.

The theoretical concentration, $\overline{C}^*$, obtained at steady state in a well mixed, ventilated room with a contaminant source of strength S is:

$$\overline{C}^* = \frac{S\langle\tau\rangle}{M} \tag{6.4}$$

where M is the mass of air in the room and $\langle\tau\rangle$ the room mean age of air measured according Section IV.5.

Measuring the effective mean contaminant concentration $\langle \overline{C}\rangle$, the distribution effectiveness is obtained using equation (2.20) and the relative contaminant removal effectiveness by:

$$\mu = \frac{\overline{C}^*}{\langle \overline{C}\rangle} = \frac{S\langle\tau\rangle}{M\langle \overline{C}\rangle} \tag{6.5}$$

This equation can be easily used in a multizone building. in this case, S is the total generation rate of pollutant, $\langle\tau\rangle$ the average room mean age and $\langle C\rangle$ the average concentration of contaminant in the building, that is the mass of contaminant, m, divided by the total mass of air in the building, M.

7. References

After the sign # are AIRBASE numbers. If the number is between square brackets [], it relates to a book containing the quoted reference. AIRBASE numbers between brackets () relate to similar texts with a reference other than the quoted one.

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Part V
Measurements on Ventilation Systems

Symbols and Units

A	area of a section of a duct	[m^2]
C	tracer mass concentration	[-]
C_{ik}	concentration of tracer k at location i	[-]
C_o	tracer concentration in the outdoor air	[-]
D	diameter (or average size) of a duct	[m]
ε_v	efficiency of the ventilation system	[-]
K	calibration constant	[-]
l	distance, length	[m]
m	injected mass of tracer	[kg]
Q	mass air flow rate	[kg/s]
Q_i	infiltration air flow rate	[kg/s]
Q_ij	air flow rate from location i to location j	[kg/s]
Q_v	fresh air flow rate	[kg/s]
Re	Reynolds number	[-]
R_s	short circuit ratio	[-]
S	section of a duct	[m^2]
s	tracer injection flow rate	[kg/s]
v	air speed in a duct	[m/s]
$\langle v \rangle$	average air speed in a duct	[m/s]
Δp	pressure differential	[Pa]
Δt	time interval	[s]
ν	kinematic viscosity	[m^2/s]
ρ	density of air	[kg/m^3]
σ_x	standard deviation of the variable x	
τ	transit time	[s]
$\langle \tau \rangle$	average transit time	[s]

1. Introduction

In the following, a ventilation system is considered to comprise a network of ducts in which air is supplied or extracted by fans or by the natural pressures caused by wind or temperature differences (stack effect). The system may be designed to return extracted air to the occupied space (recirculation), and may exhibit short circuiting, in which a proportion of the supply air moves directly to the extract side, bypassing the occupied space.

In practice, such ventilation systems are planned to fulfill a defined task, in particular to provide defined air flow rates to the ventilated spaces. However, the effective flow rates are seldom measured and when they are, large differences with respect to the planned values are often found *[Roulet, Compagnon, Jakob, 1990]*.

There are several parameters which are commonly taken to characterize a ventilation system, as follows:

- the air flow rates in the ducts,
- the overall (or nominal) air change rate of the space,
- leakage from the ductwork,
- ratio of infiltration to fresh air supply flow rate.

Methods to measure these parameters are described below. The last of these comprises a further definition of efficiency, in addition to those summarized in Part IV.

2. Measurement of the Air Flow Rate in a Duct

2.1. Summary of Measurement Methods

Common methods, used to measure air flow rates in ducts, exploit well-known relationships between flow rate and pressure drop across a restriction placed in the flow, for example a nozzle, Venturi or sharp-edged orifice *[ISO 5167, 1980]*. Alternatively, the air speed can be measured directly at a number of points lying in a cross section of the duct (a traverse), and the results 'integrated' along the traverse to give the volume flow rate *[ISO 3966, 1977]*. All of these methods have the disadvantage that a long straight section of duct, both upstream and downstream of the measurement point, is needed in order to condition the flow. Moreover, the introduction of a restriction may significantly change the air flow rate to be measured. Tracer techniques *[ISO 4053, 1977]*, *[Axley and Persily, 1988]*, *[Riffat and Lee, 1990]* which avoid these problems employ gas analyzers and measure the dilution of a tracer gas introduced into the flow, using equipment which is becoming increasingly common, robust and easy-to-use.

General techniques involving flow restriction have been described earlier (Part II, Section 3.2). Air flow in ventilation ducts is particularly suited to measurement using either the traversing or tracer gas techniques, and these are described below.

2.2. Velocity Traverse

If the velocity of the air, $\underline{v}$, is measured at enough points in the duct, the volume air flow rate can be deduced by integration over the whole area, A, of the cross section as shown:

$$\frac{Q}{\rho} = \int_A \underline{v}\, dA = \langle \underline{v} \rangle A \qquad (2.1)$$

where ρ is the density of the air.

2.2.1. Equipment to Measure Air Speed

Provided the direction of flow is parallel to the duct, which may normally be assumed, then velocity can be determined by the measurement of air speed alone.

The air speed measurement devices should be small enough to enable them to be easily inserted through small holes in duct walls. The most common examples are hot wire- or NTC- anemometers, and Pitot tubes.

The **hot wire** and **NTC anemometers** measure the temperature drop of a heated wire or of a heated resistor (with a negative temperature coefficient), which, in each case, is directly related to the temperature and speed of the air flowing over it. The sensors are heated by an electric current and

measurements are made of the voltage drop, which depends on the temperature. The temperature of still air is taken into account by the use of a reference sensor shielded from the flow. Such devices can measure speeds from 0.05 up to 5 m/s, and are well suited for speeds between 1 and 5 m/s, which are typical in ventilation ducts.

The **Pitot tube** comprises a small probe with a small hole at the front and at the side, between which the measured pressure difference is proportional to the square of the air speed. It is most accurate for air speeds in the range 10 to 50 m/s, although speeds as low as 1 m/s can be measured using a sensitive differential manometer.

2.2.2. Test Procedure

The location of the measurement in the duct should be at least 8 diameters downstream, and 3 diameters upstream of any disturbances in the flow, such as a bend in the duct or a change in cross section. Flow-straightening vanes located at 1.5 diameters upstream will improve the measurement accuracy.

Several measurements across the duct should be taken to enable integration. It is advisable to notionally divide the duct section into sub-sections of equal area and to take measurements at their centers. The ASHRAE Handbook of Fundamentals *[ASHRAE 1989]* proposes a division of 16 to 64 rectangular sub-sections for a rectangular duct, and 20 annuli for cylindrical ducts (fig. 2.1). In the latter, any asymmetry in the flow may be taken into account by taking measurements along two orthogonal directions.

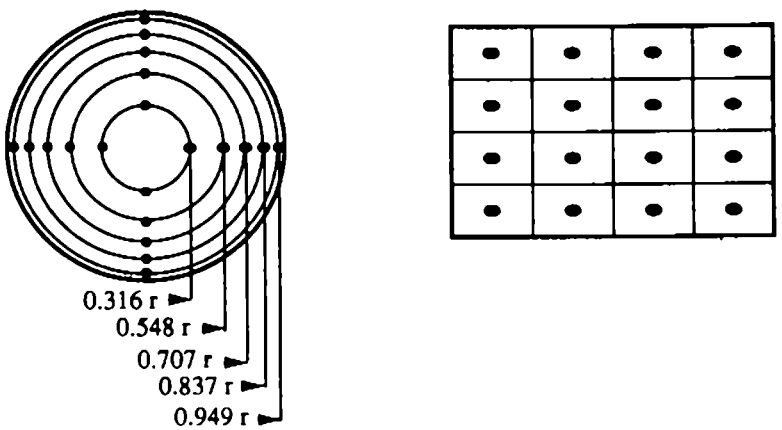

Figure 2.1: Location of the measurement points in a circular and a rectangular ducts. [ASHRAE, 1989]

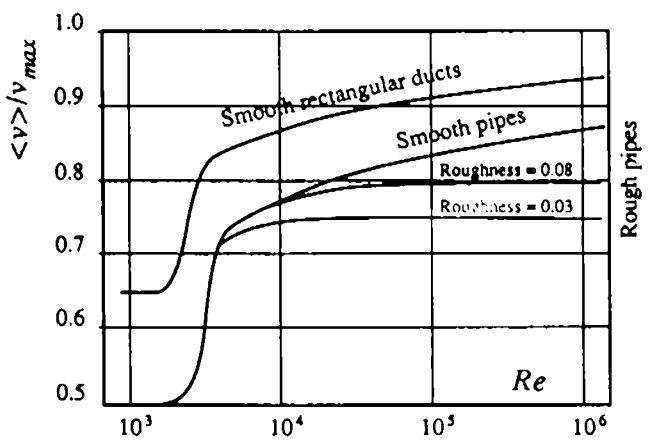

Figure 2.2: Conversion factors between average and maximum air speed in straight ducts as a function of the Reynolds Number. The roughness is the ratio of the average height of the wall irregularities to the diameter of the pipe.

For approximate measurements a velocity profile may be assumed, and it is sufficient to measure the maximum speed at the center of the section *[ISO 7145, 1982]*. Figure 2.2 can then be used to give the ratio of the average to the maximum velocity, i.e. $\langle v \rangle / v_{max}$, as a function of the Reynolds Number, *Re*,

defined as shown:

$$Re = \frac{\langle v \rangle D}{\nu} \tag{2.2}$$

where D is the diameter (or the average size) of the duct and ν the kinematic viscosity, which is about 15 10^{-6} m^2/s for air.

Since the Reynolds Number depends on the average velocity, an iterating process should be used as follows. First calculate Re using the measured maximum speed, and thus use Figure 2.2 to obtain a first approximation to $\langle v \rangle$. Use this approximation to compute a new value for Re, and repeat the whole procedure until a stable value for $\langle v \rangle$ is obtained.

2.3. The Pressure-Averaging Flow Meter

The relationship between air velocity, v, measured with a Pitot tube and the pressure differential, Δp, is:

$$v = \sqrt{\frac{2\Delta p}{\rho}} \tag{2.3}$$

Averaging the N measurements of the air velocity in a cross section results in the following expression:

$$\langle v \rangle = \frac{1}{N} \Sigma v_i = \sqrt{\frac{2}{r}} \quad \frac{\Sigma \sqrt{\Delta p_i}}{n} \tag{2.4}$$

The pressure-averaging flow meter measures an average pressure drop, $\langle \Delta p \rangle$, at several points, and the assumption is made that the square root of $\langle \Delta p \rangle$ closely approximates the sum of the square roots of the individual pressures drops, Δp_i. *[ASHRAE, 1989]*

The pressure over the measured section is averaged by means of thin tubes punctured by many small holes facing the flow, as shown in Figure 2.3.

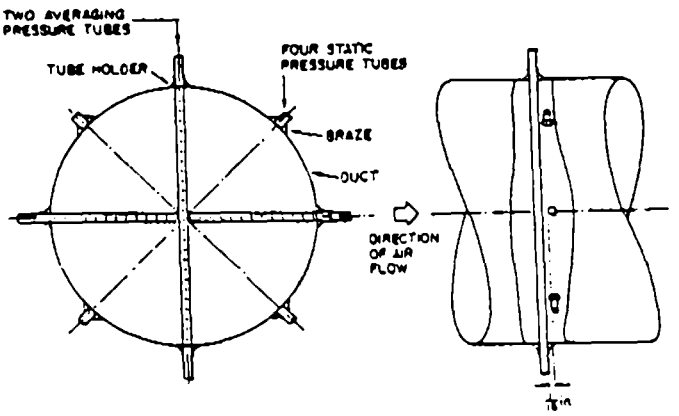

Figure 2.3: Pressure-averaging flow meter [Ma, 1967].

A correction factor, K, is used to account for imperfections in the tubes and for the deviation of the square root of the sum of pressure drops from the sum of the square roots. The average velocity is thus given by:

$$\langle v \rangle = K \sqrt{\frac{2 \langle \Delta p \rangle}{\rho}} \tag{2.5}$$

and the mass flow rate is:

$$Q = \rho A \langle v \rangle = K A \sqrt{2 \rho \langle \Delta p \rangle} \tag{2.6}$$

2.4. The Tracer Gas Dilution Method

Air flow rates in ducts can be measured using tracer gases. A continuous flow at a known rate, or a known quantity of tracer is released upstream of the length of duct. The tracer mixes with the air, and measurements of its concentration downstream are used to calculate the flow rate. The following assumptions are made: negligible leakage from the duct between the injection and sampling points; good mixing of tracer and air upstream of the sampling point; the tracer gas injection rate is small compared to the air flow rate in the duct and, the air flow rate remains constant during measurements.

Mixing should be allowed to occur over a sufficient length of duct between the injection and sampling locations. Better mixing will result in greater accuracy, but may require longer stretches of duct. In the worse case of a smooth, straight duct, with the tracer injected at the center, a mixing length equal to 50 duct diameters may be required. This may be considerably shorter if there are turbulence-generating devices present such as elbows, changes in section, fans etc. Mixing should be checked by comparing samples from different points (e.g. the wall and the duct center), and a final result obtained by taking an average.

The mixing distance may be reduced by the following methods:

- releasing the tracer simultaneously at several points across the section of the duct (e.g. for a circular duct, at 4 or 8 points on a circle 0.63 times the duct diameter),
- injecting the tracer at high speed against the air stream.

In the following method the tracer is injected at a constant rate, S [kg/s], and when a steady state is reached, the mass air flow rate, Q [kg/s], in the duct is given by:

$$Q = \frac{S}{C - C_o} \tag{3.2}$$

where C is the tracer mass concentration [kg tracer/kg mixture] at the sampling location and C_o the tracer concentration in the air upstream of injection (if non-zero). The relative error of the result can be deduced from:

$$\frac{\sigma_Q^2}{Q^2} = \frac{\sigma_S^2}{S^2} + \frac{2\sigma_C^2}{(C - C_o)^2} \tag{3.3}$$

Where σ_x is the standard deviation of the variable x.

If there is no recirculation, the time, Δt, necessary to reach this steady state is approximately given by:

$$\Delta t \cong \frac{5 A l \rho}{Q} = \frac{5 l}{\langle v \rangle} \tag{3.4}$$

where A [m^2] is the area of the section of the duct, l [m] the distance between the injection and the sampling locations and ρ the density of air [kg/m^3]. If a portion of the air in the duct is recirculated after delivery to a room, Δt may be much longer, up to 5 times the nominal time constant of air in the room.

This technique is also suited to the use of passive perfluorocarbon tracer (PFT) sources and diffusive samplers, in which a time-averaged concentration is measured.

An alternative method requires the release of a short pulse of tracer of mass m. The concentration is measured downstream and comprises a distorted form of this pulse, $C(t)$. Measurements begin at the start of injection and continue until the tracer concentration falls to the pre-injection level.

The distribution of the transit time, $f(\tau)$, and the average transit time, $\langle \tau \rangle$, can be deduced from $C(t)$ using the relations given in part IV, Table 1 for pulsed injection. The air flow rate is then:

$$Q = \frac{l S}{\langle \tau \rangle} \tag{3.5}$$

where l is the distance between the injection and the sampling points and S the section of the duct.

The transit time method may be inaccurate in complicated duct systems and is interesting only when the distribution of the transit time itself is required. The air flow rate can be deduced directly from the integral of the concentration using the integral mass balance technique *[Axley and Persily,1988]*:

$$Q = \frac{m}{\int (C(t) - C_o)\, dt} \tag{3.6}$$

where the integral is taken over the whole period for which $C \neq 0$.

An advantage of this method is that it is necessary to measure only two parameters, these being the mass of tracer injected (and not its time history), and the integral of the tracer concentration response (which need not necessarily require a temporal profile to be recorded). It is particularly suitable for techniques in which an integrated sample is taken directly, as for example by slowly filling a sample bag (grab sampling technique) or by collecting a sample on an adsorption tube (passive sampling). Any suitable tracer gas may be used and the release of gas into the duct may be achieved by the use of a syringe. This method requires only a few simple components to perform field tests.

3. Air Flow Rates in a Ventilation Network

In ventilation systems incorporating both supply and extract networks, the air flow pattern may be complex, particularly when there is recirculation or the possibility of short circuiting. Such systems can be modelled by a nodal network. If tracers are introduced at proper locations and at known flow rates, the flow rates in each pipe or branch of the network can be deduced from concentration measurements at other locations. The salient features of such a system, including heat recovery, are shown in Figure 3.1.

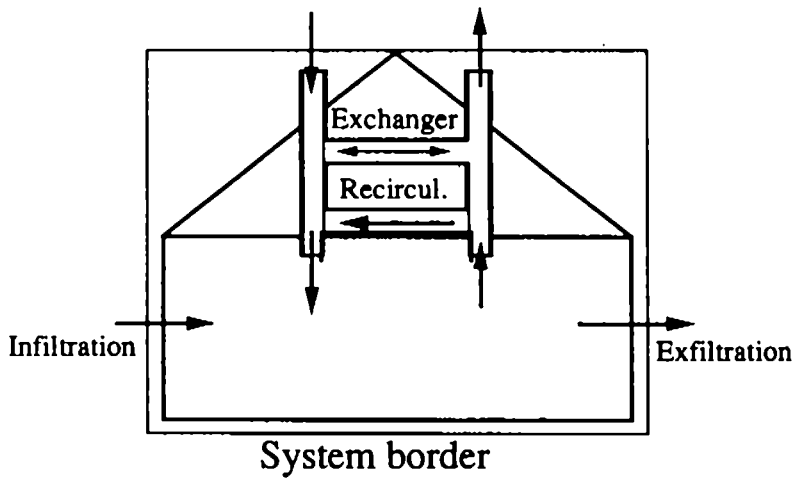

Figure 3.1: Air flows in a space ventilated using a supply and extract system with recirculation including a heat recovery system showing unintentional cross-leakage.

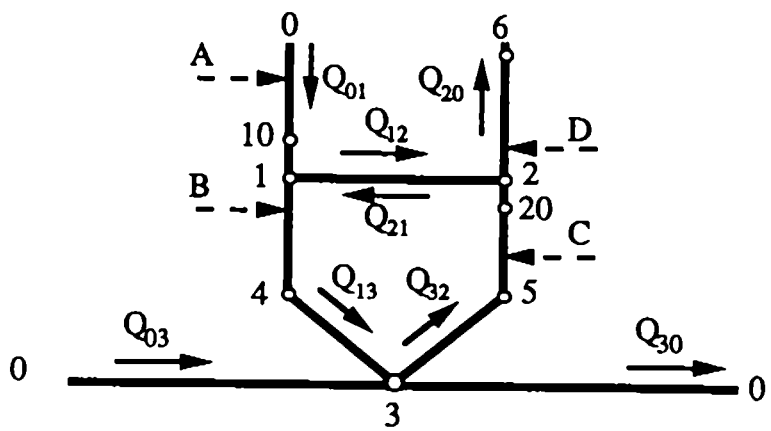

Figure 3.2: Nodal network representing a supply and extract ventilation system with short circuits (either recirculation or cross-leakage between branches). The room is node 3, with air inlets (node 4) and extracts (node 5). Node 0 is outdoors and node 6 is the exhaust point.

This system can be modelled by a network with five nodes as shown in figure 3.2, in which the possible air flows are:

Q_{01} fresh air flow into the ventilation system
Q_{20} exhaust air from the system
Q_{13} air flow at air inlets
Q_{32} air flow at air outlets
Q_{12} and/or Q_{21} short-cut air flow
Q_{03} infiltration air flow
Q_{30} exfiltration air flow

A, *B*, *C* and *D* are suitable tracer injection points.

Nodes 4 and 5 are connected to only two other nodes, hence, assuming airtight ducts:

$$Q_{14} = Q_{43} = Q_{13} \text{ and } Q_{35} = Q_{52} = Q_{32} \quad (3.1)$$

To enable measurements, tracers may be injected at points *A*, *B*, *C* and *D*. Either different tracers may be injected simultaneously at each location, or, one tracer injected successively at each (note that there must be no change in the air flows over the whole period of measurement). In the following, the tracers or the measurements are referenced by the letter corresponding to the injection location.

It will be seen later that injection point *D* is, in fact, superfluous. In addition, the concentrations at nodes 1 and 2 (inside the heat exchanger) are difficult to measure. These, however, can be replaced by measurements of other concentrations, C_{ik}, of tracer, *k*, at location *i* using the following relationships (assuming good mixing):

$$\begin{aligned} C_{4k} &= C_{1k} \text{ with } k = A, C \text{ and } D \\ C_{ek} &= C_{2k} \text{ with } k = A, B \text{ and } C \end{aligned} \quad (3.2)$$

In a well-planned ventilation system, there should be no air flow from the exhaust to intake ducts through the outdoor air. This flow rate may be introduced in the equations but is neglected below. Expressing the conservation of the mass flows at nodes 1, 2 and 3, we get:

$$Q_{01} - Q_{12} - Q_{13} + Q_{21} = 0 \quad (3.3)$$

$$+ Q_{12} - Q_{20} - Q_{21} + Q_{32} = 0 \quad (3.4)$$

$$+ Q_{03} + Q_{13} - Q_{30} - Q_{32} = 0 \quad (3.5)$$

The conservation of the mass flows of the four tracers at these nodes leads in principle to 12 equations which, together with the three equations above, gives 15 equations, which are more than sufficient to determine just 8 flows. However, some equations contain the concentrations C_{1B} or C_{2D} which cannot be measured. In addition, equations expressing the conservation of a tracer at a node upstream of its injection location involve very small coefficients (concentrations), e.g. C_{1C}. Finally, taking into account of the relationships (3.1) and (3.2), the following tracer mass balance equations remain:

$$- C_{0A} Q_{01} + C_{4A} Q_{12} + C_{4A} Q_{13} - C_{6A} Q_{21} = q_A \quad (3.6)$$

$$- C_{4A} Q_{12} + C_{6A} Q_{20} + C_{6A} Q_{21} - C_{5A} Q_{32} = 0 \quad (3.7)$$

$$- C_{4C} Q_{12} + C_{6C} Q_{20} + C_{6C} Q_{21} - C_{5C} Q_{32} = q_C \quad (3.8)$$

$$+ C_{0A} Q_{03} + C_{4A} Q_{13} - C_{5A} Q_{30} - C_{5A} Q_{32} = 0 \quad (3.9)$$

$$+ C_{0B} Q_{03} + C_{4B} Q_{13} - C_{5B} Q_{30} - C_{5B} Q_{32} = 0 \quad (3.10)$$

where q_k are the tracer gas injection flow rates [kg/s].

These five equations, together with the three equations (3.3 to 3.5), allow us to determine the eight flows, using only three tracers (the tracer D is not necessary). However, if a tracer at location *D* is used, the exhaust flow can be directly obtained:

$$Q_{20} = \frac{s_D}{C_{6D} - C_{2D}} \quad (3.11)$$

If there is no short-circuit between exhaust *e* and inlet *i*, the concentration $C_{2D} = 0$ and Q_{20} is easily determined. Nevertheless, a tracer at D is necessary only if a short-circuit between exhaust *e* and inlet *i* is likely to exist.

In most practical cases, it is possible to measure the concentration at supplementary locations in order to obtain directly some air flows. These are locations 10 and 20, just upstream of the heat exchanger in both directions. In this case:

$$Q_{01} = \frac{s_A}{C_{10A} - C_{0A}} \quad (3.12)$$

$$Q_{32} = \frac{s_C}{C_{20C} - C_{5C}} \quad (3.13)$$

From the above equations, the following results can be obtained. These results are given in the order they can be obtained, assuming that (3.12) and (3.13) are used:

$$Q_{12} = \frac{s_C + (C_{5C} - C_{6C})Q_{32}}{C_{6C} - C_{4C}} = \frac{(C_{5A} - C_{6A})Q_{32}}{C_{6A} - C_{4A}} \tag{3.14}$$

$$Q_{21} = \frac{s_A + (C_{0A} - C_{4A})Q_{01}}{C_{4A} - C_{6A}} = \frac{(C_{0C} - C_{4C})Q_{32}}{C_{4C} - C_{6C}} \tag{3.15}$$

Two expressions are given for Q_{12} and Q_{21}, where one is better conditioned than the other, according to the relative magnitudes of the two flows. For example, if Q_{12} is zero, both the numerator and denominator of the second expression in (3.15) are very small, and the second expression should be used. On the other hand, if Q_{21} is zero then the second expression in (3.14) should be used. The remaining flows are given as follows:

$$Q_{13} = Q_{01} - Q_{12} + Q_{21} \tag{3.16}$$

$$Q_{20} = Q_{12} - Q_{21} + Q_{32} \tag{3.17}$$

$$Q_{03} = \frac{(C_{4A} - C_{5A})Q_{13}}{C_{5A} - C_{0A}} = \frac{(C_{4B} - C_{5B})Q_{13}}{C_{5B} - C_{0B}} = \frac{(C_{4C} - C_{5C})Q_{13}}{C_{5C} - C_{0C}} \tag{3.18}$$

$$Q_{30} = Q_{03} + Q_{13} - Q_{32} \tag{3.19}$$

It should be noted that, when equations (3.12) and/or (3.13) can be used, the concentration of tracer B appears only in the second alternative of (3.18). This tracer is therefore not necessary and all the 8 flows can be determined with just two tracers (or two successive measurements with one tracer). However, the greatest accuracy will generally result by determining directly the flow rates of interest using more than two tracers simultaneously (or more than two measurements with a single tracer).

4. Efficiency of the Ventilation System

The most important requirement of any ventilation system is to supply a controlled flow of fresh air to the occupied space of the building. However, fresh air also enters by uncontrolled infiltration through the fabric ('envelope'). An important system efficiency can, therefore, be defined as the ratio of the supply rate of outdoor air, Q_v, due to the ventilation system, to the total air flow rate Q through the room, including the infiltration Q_i:

$$\varepsilon_v = Q_v/Q \tag{5.1}$$

for this definition, the boundary of the system is the building envelope and the outdoor inlet and exhaust ducts of the ventilation system.

To obtain this efficiency, two air flow rates should be measured: Q_v coming from the ventilation system itself and the total air flow rate, Q, through the room.

The error is estimated by:

$$\frac{\sigma^2(\varepsilon_v)}{\varepsilon_v^2} = \frac{\sigma^2(Q_v)}{Q_v} + \frac{\sigma^2(Q)}{Q^2} \tag{5.2}$$

Q can be measured in the room using the tracer gas methods described in part III or can be deduced from a complete measurement of all the flows in the ventilation network as shown in chapter V 3. In systems employing a central supply system, Q_v can be measured in the main supply duct.

For extract-only systems, a similar efficiency can be defined as the ratio of the air flow rate measured in the exhaust duct to the total air flow rate through the room. Such systems tend to depressurize the building, and we might expect the extract rate to equal the infiltration rate, i.e. an efficiency of unity 1. However, some air may leave by exfiltration (through cracks etc.), adding to the total flow rate.

The efficiency of a supply and extract system, with reference to the flows in Figure 3.2 (Chapter V.3) is:

$$e_v = \frac{Q_{13} - Q_{21}}{Q_{13} + Q_{03}} \tag{5.3}$$

where the notation of Figure 3.2 of chapter V 3 is used.

The error is estimated by:

$$\frac{\sigma^2(e_v)}{e_v^2} = \frac{\sigma^2(Q_{12}) + \sigma^2(Q_{21})}{(Q_{13} - Q_{21})^2} + \frac{\sigma^2(Q_{13}) + \sigma^2(Q_{03})}{(Q_{13} + Q_{03})^2} \tag{5.4}$$

If, and only if, $Q_{21} = 0$, i.e. no recirculation, then equation 5.3 simplifies to:

$$e_v = \frac{C_5 - C_0}{C_4 + C_0} \tag{5.5}$$

for any tracer having measurable concentrations at locations 4 and 5.

A **short-circuit ratio**, R_s, can also be defined by the ratio of the air flow rate in short circuits between intake and exhaust ducts to the main air flow:

$$R_s = \frac{Q_{12} + Q_{21}}{Q_{01}} \tag{5.6}$$

If there is no recirculation, this ratio should be zero or very small. The square of the relative standard deviation on R_s is:

$$\frac{\sigma^2(R_s)}{R_s^2} = \frac{\sigma^2(Q_{12}) + \sigma^2(Q_{21})}{(Q_{12} + Q_{21})^2} + \frac{\sigma^2(Q_{01})}{(Q_{01})^2} \tag{5.7}$$

5. Measurement of Air Tightness of a Duct or Network

To ensure the integrity of the supply air quality, and to avoid energy waste when the air is either heated or cooled, there should be negligible leaks from the transport ducts and connections. Significant energy may be wasted, for example, where leaky ductwork passes through an unheated space such as an attic, basement or crawl space. As an example, it was found that duct work to be the most significant source of leakages in US western houses, together with damperless fireplaces *[Dickerhoff, Grimsrud, Lipschutz, 1982]*. This fact is confirmed by a more recent study *[Modera, 1989]*, but some houses were nevertheless found acceptable *[Palmiter and Bound, 1991]*.

Various techniques exist to check the airtightness of such ductwork. In some countries, the air tightness of the ventilation system has to be checked when commissioning the system *[NBCF, 1987]*, but in most countries measurements are seldom carried out. In addition there is little available guidance, except an ASTM standard which is still in a draft form and therefore not yet available *[ASTM, 199?]*. Appropriate measurement methods are presented below.

5.1. Pressurization Method

The principle of this method is the same as those described in Part II. All intakes, supply terminals, exhaust and extract terminals connected to the system must be carefully sealed, e.g. using plastic sheet and adhesive tape.

Tracer gas injection and air sampling tubes may be installed at appropriate points in the system to quantify any residual flow rate, resulting from leakage. Suitable locations are the main supply or exhaust ducts.

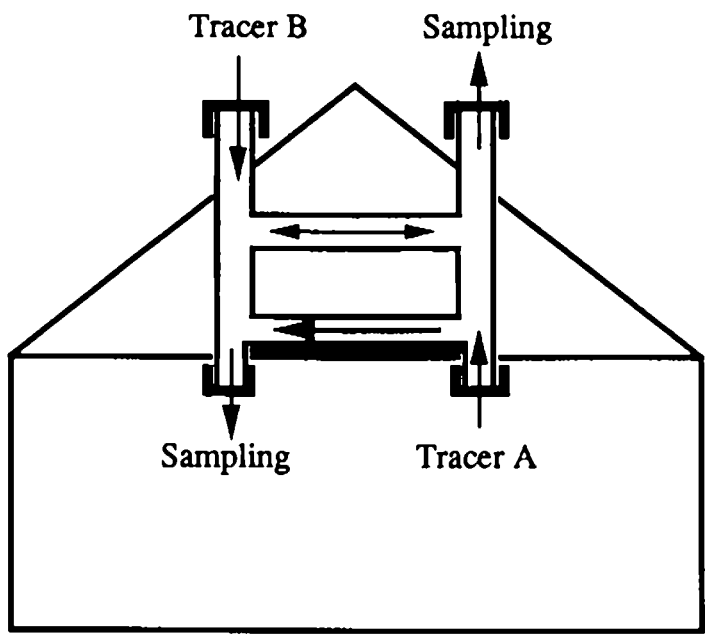

Figure 5.1: Location of tracer injection and sampling tubes for the measurement of leakage air flow rates in a ventilation system.

The system fans (or a fan added at one register if required) are used to pressurize the supply side and depressurize the exhaust side of the network. The flow, Q_L, through the fan(s) is due to leakage, and is measured as described in chapters 2 (flow meters) or 3 (with a tracer gas) together with the pressure difference, Δp, between the inside and outside of the ducts. The flow rate is the sum of all leaks downstream of the measurement point in pressurized ducts, and upstream for depressurized ducts.

A series of measurements are made at different fan speeds, and the following expression is fitted to the results:

$$Q_L = C\,\Delta p^n \tag{5.1}$$

The coefficients C and n are determined and the relationship is subsequently used to calculate the leakage rate at the service pressure difference.

5.2. Flow rate difference Method

If a duct is very leaky, the leakage can be obtained by measuring the difference between the flow rates at two locations along the flow. Since additional pressure drop should be avoided, tracers are recommended to measure the air flow rates. One tracer should be injected at a point upstream of the first location, and a second tracer injected at the first location. The concentrations of each tracer are measured after the second, downstream location, at a distance where a good mixing is achieved (see Section V.2.4). If steady flows can be assumed, two sequential measurements using a single tracer at each point may be used instead.

For depressurized ducts only one tracer is necessary. It is injected at the upstream end of the duct and its concentration is measured at both ends to give the flow rate at each.

The leakage of the whole supply or exhaust network may be determined by measuring the difference between the air flow rate in the main duct (near the fan) and the sum of all the flow rates at the individual inlet or extract terminals. For this purpose, the main air flow rate can be measured with a tracer, in the vicinity of the fan, and the flow rates at the terminals may be determined with a compensated flow meter (see part II, section 4.3.5).

Since this method the result (i.e. the leakage flow rate) is the small difference of two large numbers, this method can give rise to large uncertainties for tight or only slightly leaky ducts. Because of its ease of use, it can nevertheless be used for diagnostic purpose, to detect if the ductwork is very leaky or not.

5.3. Differential Building Pressurization

The methods described in sections 5.1 and 5.2 measure the leakage of the whole duct system. From the point of view of avoiding energy waste alone, it may be useful to measure the leaks to or from outside only, and not those between the system and the interior of the building.

For this purpose, the duct system is considered as a part of the envelope and the indirect component testing method described in part II can be used. In a first test, the closed building is pressurized after sealing the outdoor air intake and exhaust of the building, with all the registers and returns open (Figure 5.2 left). In a second test, all registers and returns are sealed (Figure 5.2 right). The difference in air flow rate between the two tests, for each pressure, is caused by duct leakage to the outside.

The major advantage of this method is the minimal requirement for equipment additional that for envelope leakage measurements. However, it is prone to inaccuracy, since the duct leakage is again obtained as the difference between the measurement of two large air flow rates.

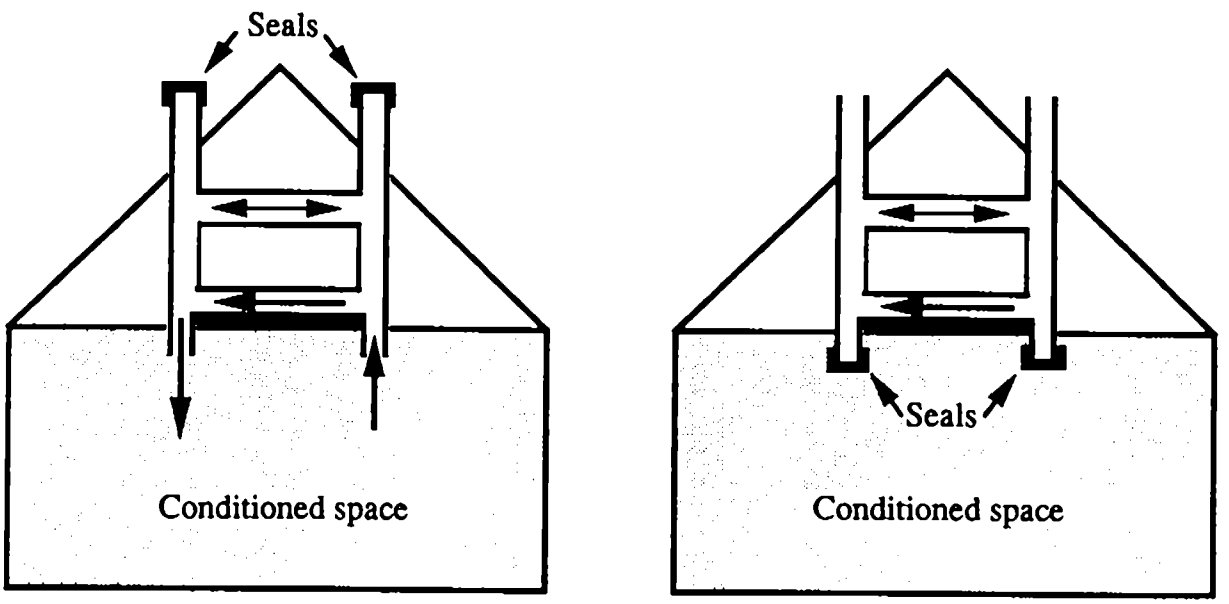

Figure 5.2: Two measurements providing, by difference, the duct leakage to outside of the conditioned space.

6. References

After the sign # are AIRBASE numbers. If the number is between square brackets [], it relates to a book containing the quoted reference. AIRBASE numbers between brackets () relate to similar texts with a reference other than the quoted one.

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Appendices

Appendix 1. Unit Conversion Tables

Introduction

SI units are used throughout this handbook. Non-SI units are however of general use in air infiltration and ventilation, like the air change rate in 1/hour or the US units. To expedite the units translations, some tables are given below. Only physical quantities which are of general use in air infiltration and ventilation measurement techniques are listed.

The figures given in the tables are multiplying factors transforming values expressed in units of the first column into values expressed in the first row units. Example: 1 cm = 0.01 m.

A 1.1. Multiples and Sub-multiples

Multiples			Sub-multiples		
Prefix	Symbol	Factor	Prefix	Symbol	Factor
peta~	P	10^{15}	femto~	f	10^{-15}
tera~	T	10^{12}	pico~	p	10^{-12}
giga~	G	10^{9}	nano~	n	10^{-9}
mega~	M	10^{6}	micro~	μ	10^{-6}
kilo~	k	10^{3}	milli~	m	10^{-3}
hecto~	h	10^{2}	centi~	c	10^{-2}
deca~	da	10^{1}	deci~	d	10^{-1}

A 1.2. Length

Name		m	cm	in	ft	yd
1 meter	m	1	100	39.37008	3.28084	1.093613
1 centimeter	cm	0.01	1	0.3937008	0.0328084	0.01093613
1 inch	in	0.0254	2.54	1	1/12	1/36
1 foot	ft	0.3048	30.48	12	1	1/3
1 yard	yd	0.9144	91.44	36	3	1

A 1.3. Area

Name	Symbol	m^2	cm^2	sq in	sq ft	sq yd
1 square meter	m^2	1	10^{4}	1550	10.7639	1.19599
1 square centimeter	cm^2	10^{-4}	1	0.3937008	0.0328084	0.01093613
1 square inch	sq in	$6.4516\ 10^{-4}$	6.4516	1	1/144	1/1296
1 square foot	sq ft	0.092903	929.0304	144	1	1/9
1 square yard	sq yd	0.836127	8361.27	1296	9	1

A 1.4. Volume

Name	Symbol	m^3	l	ml *or* cm^3	cu yd	cu ft	cu in
cubic meter	m^3	1	1'000	10^6	1.30795	35.31464	5085.308
liter	l	0.001	1	1'000	$1.308\ 10^{-3}$	0.035315	5.085308
milliliter†	ml	0.000001	0.001	1	$1.308\ 10^{-6}$	$35.32\ 10^{-6}$	0.00509
cubic yard	cu yd	0.76455551	764.5555	764555.5	1	27	3888
cubic foot	cu ft	0.02831687	28.31687	28316.87	0.037037	1	144
cubic inch	cu in	$196.6\ 10^{-6}$	0.196645	196.6449	$257.2\ 10^{-6}$	$6.944\ 10^{-3}$	1

†: the Milliliter is equal to the cubic centimeter.

A 1.5. Mass

Name	Symbol	kg	g	lb	oz	gr
1 kilogram	kg	1	1'000	2.204623	35.27396	15'432
1 gram	g	0.001	1	$2.205\ 10^{-3}$	0.03527396	15.43
1 pound	lb	0.45359229	453.5923	1	16	700
1 ounce	oz	0.02834952	28.34953	0.0625	1	437
1 grain	gr	$64.79\ 10^{-6}$	0.064799	$142.9\ 10^{-6}$	$2.2857\ 10^{-3}$	1

A 1.6. Time

Name	Symbol	s	mn	h	d	yr
1 second	s	1	1/60	1/3600	1/86400	$31,688\ 10^{-9}$
1 minute	mn	60	1	1/60	1/1440	$1.90133\ 10^{-6}$
1 hour	h	3600	60	1	1/24	$114.08\ 10^{-6}$
1 day	d	86'400	1440	24	1	$2.73791\ 10^{-3}$
1 year	yr	31'556'926	$526\ 10^3$	8765	365.25	1

A 1.7. Pressure

Name	Symbol	Pa	mbar	mm H_2O	in H_2O	psi
1 Pascal	Pa	1	0.01	0.102	0.004	$145.037\ 10^{-6}$
1 millibar	mbar	100	1	10.2	0.422	$14.5037\ 10^{-3}$
1 mm water column	mm H_2O	9.81	0.0981	1	0.0393	$1.42\ 10^{-3}$
1 inch water column	in H_2O	249	2.5	25.4	1	$36\ 10^{-3}$
1 pound per in^2	lb/in^2 *or* psi	6'894.76	68.9476	703	27.7	1

A 1.8. Volume Flow Rate

Symbol	m^3/s	l/mn	m^3/h	cu ft/s	cu ft/mn	cu ft/h
m^3/s	1	60'000	3'600	35.3146	2118.878	127132.693
l/mn	$16.667\ 10^{-6}$	1	0.06	$588.58\ 10^{-6}$	0.0353146	2.11887822
m^3/h	$277.78\ 10^{-6}$	16.666667	1	0.00980962	0.58857728	3
cu ft/s	0.02831687	1699.0122	101.9407335	1	60	3600
cu ft/mn	$471.95\ 10^{-6}$	28.316870	1.699012225	0.01666667	1	60
cu ft/h	$7.87\ 10^{-6}$	0.47194784	0.028316870	277.7810^{-6}	0.01666667	1

A 1.9. Mass Flow Rate

Symbol	kg/s	kg/mn	kg/h	lb/s	lb/mn	lb/h
kg/s	1	60	3600	2.204623	132.27738	7'936.643
kg/mn	0.01666667	1	60	0.03674372	2.204623	132.27738
kg/h	$277.78\ 10^{-6}$	0.01666667	1	$612.4\ 10^{-6}$	0.03674372	2.204623
lb/s	0.45359229	27.2155375	1632.932	1	60	3600
lb/mn	0.00755987	0.45359229	27.21554	0.01666667	1	60
lb/h	$125.1\ 10^{-6}$	0.00755987	0.4535923	$277.8\ 10^{-6}$	0.01666667	1

A 1.10.Tracer Concentration

The conversion between units of tracer (or contaminant) concentration requires the knowledge of the densities of tracer (or contaminant) and air or of their molecular masses. Therefore, formulas are given below instead of tables. The following notations are used, the quantities being taken in an homogeneous volume, V:

C_k mass concentration of tracer k . . . . . [kg/kg]
c_k volume concentration of tracer k . . . . . [m^3/m^3]
χ_k volumetric mass of tracer k (also called concentration) . . . . . [kg/m^3]
m mass of air . . . . . [kg]
m_k mass of tracer k . . . . . [kg]
M_k molecular mass of tracer k . . . . . [kg/Mole]
M molecular mass of air=: $M = 0.0289645$ . . . . . [kg/Mole]
p atmospheric pressure . . . . . [Pa]
R molar gas constant: $R = 8.31396$ . . . . . [J/(mole.K)]
T absolute temperature . . . . . [K]
V volume of air . . . . . [m^3]
V_k volume of tracer k . . . . . [m^3]
ρ density of air : $\rho = m/V$ . . . . . [kg/m^3]
ρ_k density of tracer k : $\rho_k = m_k/V_k$ . . . . . [kg/m^3]

The definitions of the various concentrations are:

Mass concentration

$$C_k = \frac{m_k}{m + m_k} = \frac{\rho_k V_k}{\rho V + \rho_k V_k} \qquad \text{(A1.1)}$$

Volume concentration

$$c_k = \frac{V_k}{V + V_k} \qquad \text{(A1.2)}$$

Volumetric mass

$$\chi_k = \frac{m_k}{V + V_k} = \rho_k c_k \qquad \text{(A1.3)}$$

Since, for usual tracer gas measurements or for usual pollution $C_k << 1$, and therefore $V_k << 1$, the following approximations can be used:

$$C_k = \frac{\rho_k}{\rho} c_k \qquad \text{(A1.4)}$$

$$c_k = \frac{\rho}{\rho_k} C_k \qquad \text{(A1.5)}$$

$$\chi_k = \rho C_k \text{ (A1.6)}$$

The tracer density is defined by $\rho_k = m_k/V_k$ where the volume, V_k, is defined at atmospheric pressure, p. Using the perfect gas law for tracer k, the density of tracer k can be computed:

$$\rho_k = \frac{p M_k}{R T} \qquad \text{(A1.5)}$$

The same is valid for air, using its average molecular mass, $M = 0.0289645$ kg/mole. Equations (A1.3) becomes:

$$C_k = \frac{M_k}{M} c_k \qquad \text{(A1.6)}$$

and the so-called "concentration" or volumetric mass in [kg/m^3] is:

$$\chi_k = \frac{p M_k}{R T} c_k \approx \frac{p M}{R T} C_k \qquad \text{(A1.4)}$$

The concentration in [ppm] (parts per million) is in most cases a volume concentration, c_k. As a special example using common units, the following relation gan be given for a gas at 25 °C and 101.3 kPa:

$$\chi_k \text{ [mg/m}^3\text{]} = \frac{M_k \text{ [g]} \times c_k \text{ [ppm]}}{24.45}$$

Appendix 2. Error Analysis

A 2.1. Introduction

Any measurement result should be given with its confidence interval or its domain of probable error. This appendix presents some methods to calculate the confidence interval of the interpreted result of measurements when the probable error of the measurement is known.

A 2.1.1 Scope of the Error Analysis

The accuracy of any measurement depends on the conditions in which the measurement is done, on the quality of the measuring instrument and on the skill of the personal making the measurement. This accuracy cannot be infinite, and any measurement result contains a given uncertainty. That means that the result is not absolute, but it is always possible to state that the real value is contained, with a given probability, within some confidence limits. Since this confidence interval may be large, there is no sense to give the result of a measurement without any information on its reliability.

A measurement result is valid only with its confidence interval.

Generally, an instrument does not give directly the required information. In most of the cases, several measurement are combined to obtain the needed value. For example, in tracer gas measurements, several concentrations, gas flows, time and volume measurements are combined in a formula to get the air flow rates. The errors accompanying the measured values are propagated through the interpretation formulas and finally give a probable error on the final result.

In this chapter, some methods allowing to estimate the error on the result are presented. Note that only the instrumental and random errors are treated here. Bias caused by misuse of the instruments or by a lack of precautions are not treated here.

A 2.1.2 Definitions

Let us call x the result of a measurement. If several measurements of the same physical quantity are made, the results x_i of these measurements will not be all equal. The confidence interval or the probable error can be expressed by two ways:

- The **absolute error** is expressed in the same units as the physical quantity:

  $$\text{Measurement} = x \pm dx \text{ [unit]} \qquad \text{(A2.1)}$$

  and the confidence interval goes from $x - \delta x$ to $x + \delta x$.

- The **relative** error is the ratio of the absolute error to the measured value:

  $$e = \delta x / x \qquad \text{(A2.2)}$$

  which can be expressed in percent by multiplying e by 100.

The inverse relation is:

$$\delta x = x\, e \qquad \text{(A2.3)}$$

The results should always be given with their confidence interval (or with an estimate of the possible error) and with the unit used. The digits in the results shall all be significant:

Correct: Length = 420 ± 10 mm or 420 mm within 2%

Not correct: Length = 421.728 ± 9.511 mm or 421.728 within 2.255%

A 2.2. A Few Statistics

A good error analysis cannot be done without using some basic statistical theory. There are simplified methods, which unfortunately give often too large an error domain. The statistical methods allows one to obtain more information on the reliability of the results.

A 2.2.1 Definitions

Because of random reading errors and uncontrolled perturbations, the test values will follow a given distribution. We can model such distributions by treating x as a stochastic variable.

The **probability density function** $f(X)$ of the variable x is the probability to find x between X and $X + dx$.

Its integral $F(X)$ is the probability of having $x < X$:

$$F(X) = \text{prob}\,(x<X) = \int_{-\infty}^{X} f(x)\,dx \qquad \text{(A2.4)}$$

The **lower significance limit** is the value X_l for which $F(X_l) = p$, where p is a given probability. The upper significance limit is the value X_s for which $F(X_s) = 1\text{-}p$.

The **confidence interval** $[X_l, X_s]$ is the range between the lower and the upper significance limit. The probability to find x in this interval is $P = 1 - 2p$.

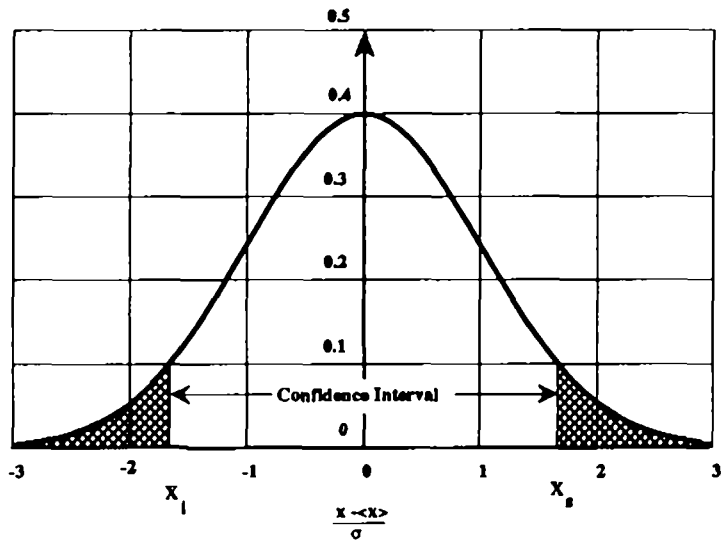

Figure A 2.1: Significance limits and confidence interval.

A 2.2.2 Average

If the same importance is given to all the results, an estimate of the **average** of the variable x based on N measurements is calculated by:

$$\langle x \rangle = \frac{\Sigma_i x_i}{N} \qquad \text{(A2.5)}$$

where the sum runs over these N measurements ($i = 1, \ldots N$).

If we will give more importance to some measurements than to the others, a weight w_i can be attributed to each value x_i and the **weighted average** is calculated by:

$$\langle x \rangle = \frac{\Sigma_i w_i x_i}{\Sigma_i w_i} \qquad \text{(A2.6)}$$

A 2.2.3 Variance and Standard Deviation

A figure representing the importance of the scattering around the average value is the **mean square deviation or variance**:

$$S_x = \frac{\Sigma(x_i - \langle x \rangle)^2}{(N-1)} = \frac{\Sigma(x_i^2) - N\langle x \rangle^2}{(N-1)} \qquad \text{(A2.7)}$$

The square root of S_x is the estimate s_x of the standard deviation σ_x:

$$s_x = \sqrt{(S_x)} \approx \sigma_x \qquad \text{(A2.8)}$$

The larger the number of measurements, the better is the estimate.

A 2.2.3 Covariance

An estimate s_{xy} of the covariance σ_{xy} of two random variables x and y, of which N measurements x_i and y_i were done is calculated by:

$$s_{xy} = \frac{\Sigma(x_i - \langle x \rangle)(y_i - \langle y \rangle)}{N-1} = \frac{\Sigma(x_i y_i) - N\langle x \rangle\langle y \rangle}{N-1} \qquad \text{(A2.9)}$$

This figure gives the tendency of two quantities to vary together. If these two variables are totally independent, the covariance will be zero. The covariance of a quantity with itself is the variance, already defined in equation (A2.7).

A 2.2.4 Statistical Distributions

There are numerous probability distributions having a mathematical model. It is not the place here to present all of them. These can be found in the specialized handbooks mentioned in the references Section A2.6. The two most used distributions, which are also used afterwards to estimate the confidence intervals, are presented below.

Normal or Gaussian distribution

The probability density function of this distribution is:

$$f(c) = \frac{1}{\sigma\sqrt{(2\pi)}} \exp\left(\frac{-c^2}{2}\right) \qquad \text{where } c = \frac{x - \mu}{\sigma} \qquad \text{(A2.10)}$$

where μ is the average and σ the standard deviation of the variable x.

The probability of the normal distribution is:

$$F(c) = .5[1 + \mathrm{erf}(c/\sqrt{2})] \qquad \text{(A2.11)}$$

where the error function erf(x) is:

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-\xi^2)\, d\xi \qquad \text{(A2.12)}$$

with erf(-x) = - erf(x).

The confidence interval [-c, c] of the normal distribution is obtained by solving the equation:

$$P = \mathrm{erf}(c/\sqrt{2}) \qquad \text{(A2.13)}$$

for a given value of P.

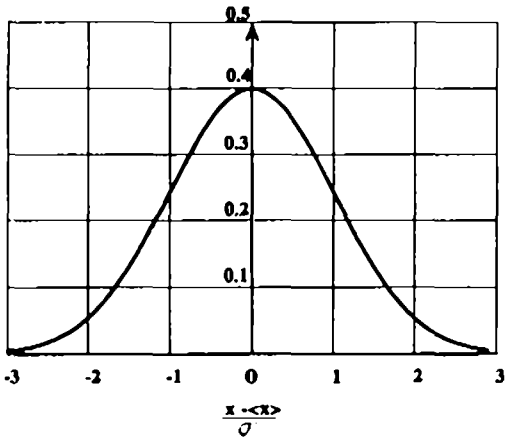

Figure A 2.2: Normal (or Gauss) distribution.

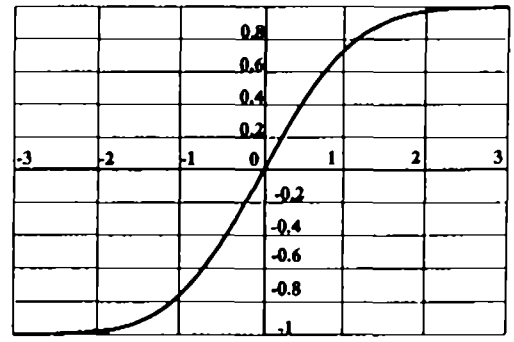

Figure A 2.3: Error function

The Student distribution

If the normalized variable

$$c = (x - \mu)/\sigma$$

is calculated using the estimate s of the standard deviation (based on n+1 measurements) instead of the exact value σ (which is not known in practice), then this estimate of the normalized variable;

$$t = (x - \mu)/s \qquad \text{(A2.14)}$$

has a probability density function:

$$f(t,n) = \frac{\Gamma((n+1)/2)}{\Gamma(n/2)\sqrt{(n\pi)}} (1 + t^2/n)^{-(n+1)/2} \qquad \text{(A2.15)}$$

where the gamma function $\Gamma(x/2)$ is:

if x is even: $\Gamma(x/2) = (x/2\text{-}1)(x/2 - 2)\cdot\ldots\cdot 3\cdot 2\cdot 1$ and $\Gamma(x/2) = (x/2\text{-}1)(x/2 - 2)\cdot\ldots\cdot 1/2$ if x is odd.

If n is large, the Student distribution tends to the normal distribution.

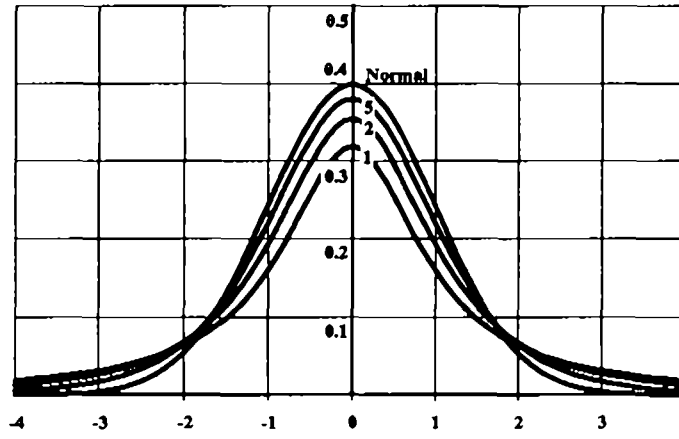

Figure A 2.4: Student distribution f(t, 1, 2 and 5) compared to the normal distribution.

The confidence interval $[-T,T]$ where $T = T(P,\nu)$ of the Student distribution cannot be expressed analytically. It can be found in Table A 2.1 (or in more details in statistical tables like *[Diem and Lentner, 1970]*) or by the use of the following approximation:

Let (A2.16)

$$V = \sqrt{[2 \cdot \ln(2/(1-P))]}$$

$$Z = V - \frac{2{,}515517 + V(0{,}802853 + 0{,}010328\,V)}{1 + V[1{,}432788 + V(0{,}189269 + 0{,}001308\,V)]}$$

$$T = Z(1 + (Z^2 + 1)/4v + (3 + Z^2(6 + 5\,Z^2))/96v^2 + [-15 + Z^2(17 + Z^2(19 + 3Z^2))]/384\,v^3 + [-945 + Z^2(-1920 + Z^2(1482 + Z^2(776 + 79\,Z^2)))]/(92160\,v^4))$$

p	0.8	0.9	0.95	0.99	0.995	0.999
n						
1	3.078	6.3138	12.706	63.657	127.32	636.619
2	1.886	2.9200	4.3027	9.9248	14.089	31.598
3	1.638	2.3534	3.1825	5.8409	7.4533	12.924
4	1.533	2.1318	2.7764	4.6041	5.5976	8.610
5	1.476	2.0150	2.5706	4.0321	4.7733	6.869
6	1.440	1.9432	2.4469	3.7074	4.3168	5.959
7	1.415	1.8946	2.3646	3.4995	4.0293	5.408
8	1.397	1.8595	2.3060	3.3554	3.8325	5.041
9	1.383	1.8331	2.2622	3.2498	3.6897	4.781
10	1.372	1.8125	2.2281	3.1693	3.5814	4.5787

***Table A 2.1:** Two-sided confidence limits T(P, n) for a Student distribution.*

A 2.2.5 Confidence Interval of the Gaussian Distribution

Assuming that a measurement x_i is a combination of the "true" value μ and a random error e_i, we have:

$$x_i = \mu + e_i$$

By measuring x_i, we expect to find the best estimate of μ. This can be done by performing N>1 measurements and computing their average. This average $\langle x \rangle$ is the estimate of the "true" value μ:

$$\langle x \rangle = \frac{\Sigma x_i}{N}$$

Let us recall that the confidence interval is the interval which has a given probability P (e.g. 95 %) to contain the "true" value. In other terms, the probability to be wrong, that is that the "true" value be outside this confidence interval, is the error probability $p = 1 - P$.

What we want now is precisely to give the confidence interval around $\langle x \rangle$ which will contain μ with a fair probability. The value of this confidence interval depends on the probability distribution of the measured values. In principle, a reasonable distribution function should be chosen, adjusted on the measurements and the validity of this adjustment should be tested with the χ^2 test.

On most cases however, and mainly when the number of the measurements is large, a normal distribution with a mean μ and a standard deviation σ can be assumed for the results of the measurements. Under this assumption, the confidence limit of the true value is given by:

$$I_C = \frac{s}{\sqrt{N}} T(P, \text{N}-1) \qquad \text{(A2.17)}$$

where s is the estimate of σ and T(P, N–1) is the confidence interval of the Student distribution with N–1 degree of freedom.

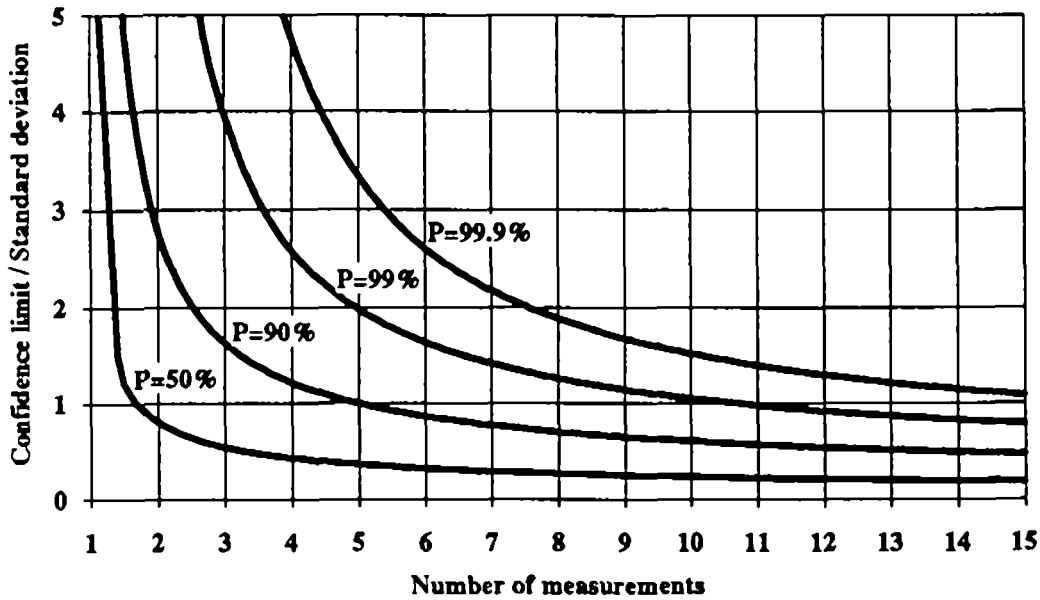

Figure A 2.5: Value of the factor T(P, N−1)/$\sqrt{N}$ for various values of P.

We can hence state:

$$\mu = \langle x \rangle \pm I_c$$

P is the probability that the confidence interval contains the "true" value. P is chosen a priori, in practice between 0.9 and 0.99, depending on the degree of confidence needed. The higher the probability, the broader is the confidence interval $[-I_c, I_c]$.

Note that the confidence interval of the "true" value stabilizes to a value to close to the standard deviation if more than 7 measurements are performed.

A 2.3. Error Analysis

A 2.3.1 What is the Problem?

If several measurements are combined to obtain the needed results, the errors should also be combined the proper way to get the resultant error. In other words, the problem is the following:

Suppose that we need several results $y_1, y_2, \ldots y_j, \ldots y_M$, each of them depending on measurements of several variable $x_1, x_2, \ldots x_i, \ldots x_N$:

$$y_j = f_j(x_1, x_2, \ldots x_i, \ldots x_N) \qquad \text{(A2.18)}$$

Here, j (j = 1 to M) enumerates the various results (e.g. M different air flow rates) and i (i = 1 to N) enumerates the variables on which the results depend (e.g the tracer gas concentrations and flow rates or pressures and conductances).

If the measurements x_i each have an absolute error δx_i, which are the errors δy_j on the results y_j?

A 2.3.2 Most Simple Error Analysis

The simplest rule, which is taught everywhere, is the following: the error δy on the result is estimated by replacing, in the total differential df of the function f, the infinitely small increments dx_i by the absolute error δx_i and by summing the absolute values:

$$\delta y_j = \Sigma_i \left| \frac{\partial f_j}{\partial x_i} \, \delta x_i \right| \qquad \text{(A2.19)}$$

If only arithmetical operations are used, the rules simplifies to the following:

- If the result is obtained by adding or subtracting the measurements, the absolute error on the result δy is the sum of the absolute errors δx of each measurement.

- If the result is obtained by multiplying or dividing measured data, the relative error on the result, $\delta y/y$, is the sum of the relative errors $\delta x/x$ on the measurements.

A 2.3.3 Estimate of the Variance

The most simple method illustrated above is very rough, since it overestimates the confidence interval by supposing that all the errors in the measurements pull the result in the same direction, which is highly improbable. A stochastic interpretation is then needed to take account of randomly distributed errors.

If the variances, s_{xi} and the covariances $s_{xi,xj}$ of the measurements are known or estimated, the covariances on the results, $s_{yk,yl}$ is, in a first approximation:

$$s_{yk,yl} = \Sigma_i \Sigma_j \frac{\partial f_k}{\partial x_i} \frac{\partial f_l}{\partial x_j} s_{xi,xj} \qquad \text{(A2.20)}$$

The variance of a given result is then:

$$(s_{yk})^2 = \Sigma_i \Sigma_j \frac{\partial f_k}{\partial x_i} \frac{\partial f_k}{\partial x_j} s_{xi,xj} \qquad \text{(A2.21)}$$

and if the measured variables are independent (that is if $s_{xi,xj}=0$ when $i \neq j$), this simplifies to:

$$(s_{yk})^2 = \Sigma_i \left(\frac{\partial f_k}{\partial x_i}\right)^2 (s_{xi})^2 \qquad \text{(A2.22)}$$

The corresponding confidence intervals are then easily obtained by multiplying these results by the Student coefficient $T(P,\infty)$.

Example:

This simple example clearly shows the information one can obtain from a statistical error analysis.

Suppose that we intend to verify the mass of a 20 kg coffee bag, but we have only a poor balance with a maximum limit of 2 kg and an accuracy of 20 g (1%). We shall then weight about 10 times 2 kg of coffee beans and make the sum of these weights. Suppose that this sum is 19,86 kg, or 140 g seems to be missing. Does the merchant steals from us?

Using the most simple method of section 3.2, we will estimate that the error might be 10·20 = 200 g. The real weight is hence between 19,66 and 20,06 kg. Therefore, we cannot be sure that there are 150 g missing.

We can estimate the standard deviation (assuming that the standard deviation on the measurement is 20 g) by $s^2 = 10 \cdot 20^2 = 4000$ *hence* $s = \sqrt{(4000)} = 63$ *g.*

The estimated weight has a probability P to be significantly different of the real weight, supposed to be 20 kg, if:

$$(P_{est} - 20\ kg) = s\,T(P, N\text{-}1) = I_c$$

Then:

Confidence probability	*T(P,10-1=9)*	*Confidence interval*
0.90	*1.83*	*115 g*
0.95	*2.26*	*142 g*
0.99	*3.25*	*205 g*

The probability that the merchant steals from us is about 95 %, since for this value of P, the confidence interval is close to the difference between the measurement and the announced weight.

A 2.3.4 Linear Equations Systems

The problem : To interpret the results of an experience, often we have to solve a system of equations:

$$\underline{\underline{A}}\,\underline{y} = \underline{x} \qquad \text{(A2.23)}$$

where components of the vector $\underline{x}$ and the coefficients in the matrix $\underline{\underline{A}}$ (which are the results of the measurements) are perturbed by random errors which can be represented by a vector $\underline{\delta x}$ and a matrix $\underline{\underline{\delta A}}$. The question is: which is the resulting error $\underline{\delta y}$ on the vector $\underline{y}$, which is the vector containing the final results?

If the matrix $\underline{\underline{\delta A}}$ and the vector $\underline{\delta x}$ were known in a given case, we could write:

$$(\underline{\underline{A}} + \underline{\underline{\delta A}})(\underline{y} + \underline{\delta y}) = \underline{x} + \underline{\delta x} \qquad \text{(A2.24)}$$

and, taking (23) into account, we could solve:

$$\underline{\delta y} = (\underline{\underline{A}} + \underline{\underline{\delta A}})^{-1} (\underline{\delta x} - \underline{\underline{\delta A}}\ \underline{y}) \qquad \text{(A2.25)}$$

However, equation (24) can not be used to determine the absolute error or a statistical standard deviation. For that latter purpose, we can use (24) several times in a Monte-Carlo process, varying the components of $\underline{\underline{\delta A}}$ and $\underline{\delta x}$ at random but according to their probability density function. This provides several vectors $\underline{\delta y}$ from which an estimate of the probability density functions of the components can be calculated. However this procedure is time-consuming and, assuming a normal distribution of the measurement methods, simpler methods are available, which are described next.

Complete error analysis: The requested final result is calculated using:

$$\underline{y} = \underline{\underline{A}}^{-1}\ \underline{x} \text{ hence } y_i = \Sigma_j\, \alpha_{ij}\, x_j \qquad \text{(A2.26)}$$

where the coefficients α_{ij} are those of the inverse matrix $\underline{\underline{A}}^{-1}$. The error calculated with the most simple (or the differential) method will then be:

$$\delta y_i = \Sigma_k \left| \frac{\partial y_i}{\partial x_k}\, \delta x_k \right| + \Sigma_{kl} \left| \frac{\partial y_i}{\partial a_{kl}}\, \delta a_{kl} \right|$$

$$= \Sigma_k \left| \alpha_{ik}\, \delta x_k \right| + \Sigma_{kl} \left| \Sigma_j \frac{\partial \alpha_{ij}}{\partial a_{kl}}\, x_j\, \delta a_{kl} \right|$$

Since (see note at the end of this Appendix, page A16)

$$\frac{\partial \alpha_{ij}}{\partial a_{kl}} = -\,\alpha_{ik}\, \alpha_{lj}$$

we get finally:

$$\delta y_i = \Sigma_k \left| \alpha_{ik}\, \delta x_k \right| + \Sigma_{kl} \left| \Sigma_j - \alpha_{ik}\, \alpha_{jl}\, x_j\, \delta_{kl} \right| \qquad \text{(A2.27)}$$

If the variances and covariances $s^2_{xk,xl}$, $s^2_{akl,amn}$ and $s^2_{akj,xm}$ are known, the covariance of the results $s^2_{yi,yj}$ is well estimated using a first order Taylor's expansion *[Bevinton, 1969]*. We get:

$$s^2_{yi,yj} = \Sigma_{klmn} \frac{\partial y_i}{\partial a_{kl}} \frac{\partial y_j}{\partial a_{mn}}\ s^2_{akl,amn}$$

$$+ \Sigma_{kl} \frac{\partial y_i}{\partial x_k} \frac{\partial y_j}{\partial x_l}\ s^2_{xk,xl}$$

$$+ \Sigma_{klm} \left(\frac{\partial y_i}{\partial a_{kl}} \frac{\partial y_j}{\partial x_m} + \frac{\partial y_j}{\partial a_{kl}} \frac{\partial y_i}{\partial x_m} \right)\ s^2_{akl,xm}$$

the partial derivatives are computed as above and we get finally:

$$s^2_{yi,yj} = \Sigma_{klmn}\, \alpha_{ik}\, y_l\, \alpha_{jm}\, y_n\, s^2_{akl,amn} + \Sigma_{kl}\, \alpha_{ik}\, \alpha_{jl}\, s^2_{xk,xl} \qquad \text{(A2.28)}$$

$$+ \Sigma_{klm} \left(-\,\alpha_{ik}\, y_l\, \alpha_{jm} - \alpha_{jk}\, y_l\, \alpha_{im} \right) s^2_{akl,xm}$$

which simplifies, if the variables are independent (that is if the covariances are zero, which is not always the case):

$$s^2_{yi,yj} = \Sigma_{kl}\, \alpha_{ik}\, \alpha_{jk}\, y^2_l\, s^2_{akl,akl} + \Sigma_k\, \alpha_{ik}\, \alpha_{jk}\, s^2_{xk,xk} \qquad \text{(A2.29)}$$

A 2.3.5 Upper Bound of the Errors

The vector $\underline{\delta y}$ contains a large number of values. It would be helpful to represent the error by a single value. To obtain such a single value, we need the following definitions, which can be found in the specific mathematical literature (e.g. *[Dietmar]*).

Vectorial norms and matrix norms: **The norm $\|\underline{x}\|$ of a vector $\underline{x}$ is any operation of $\mathbf{R}^n$ in $\mathbf{R}$ satisfying:**

$\|\underline{x}\| \geq 0$ et $\|\underline{x}\| = 0$ if and only if $\underline{x} = \underline{0}$

$\|c\underline{x}\| = |c|\,\|\underline{x}\|$ for any $c \in R$ (A2.30)

$\|\underline{x}+\underline{y}\| \leq \|\underline{x}\| + \|\underline{y}\|$

For example, the euclidian norm, which corresponds best to the standard deviation:

$$\|\underline{x}\|_2 = \sqrt{(\Sigma x_i^2)} \quad \text{(A2.31)}$$

complies with the relations (27), but there are many others, like $\|\underline{x}\|_1 = \Sigma\,|x_i|$ or $\|\underline{x}\|_\infty = \max(|x_i|)$.

Norm $\|\underline{A}\|$ of a matrix $\underline{A}$: any application $N(\underline{A}) \Rightarrow \|\underline{A}\| \in R$ satisfying:

$\|\underline{A}\| \geq 0$ et $\|\underline{A}\| = 0$ if and only if $\underline{A} = \underline{0}$

$\|c\underline{A}\| = |c|\,\|\underline{A}\|$ for any $c \in R$ (A2.32)

$\|\underline{A}+\underline{B}\| \leq \|\underline{A}\| + \|\underline{B}\|$

$\|\underline{A}.\underline{B}\| \leq \|\underline{A}\|.\|\underline{B}\|$

The matrix norm $\|\underline{A}\|$ is **consistent** with the vectorial norm $\|\underline{x}\|$ if:

$$\|\underline{A}\,\underline{x}\| \leq \|\underline{A}\|.\|\underline{x}\| \text{ for any } \underline{x} \quad \text{(A2.33)}$$

and the matrix norm is **subordinated** to the vectorial norm $|\underline{x}|$ if:

$$\|\underline{A}\| = \max(\|\underline{A}\,\underline{x}\| / \|\underline{x}\|) \text{ for any } \underline{x} \neq \underline{0} \quad \text{(A2.34)}$$

The subordinated norm is the smallest matrix norm compatible with the norm $\|\underline{x}\|$.

For example, the norm $\|\underline{A}\|_2$, defined as:

$$\|\underline{A}\|_2 = \sqrt{\mu_1} \quad \text{(A2.35)}$$

where $\sqrt{\mu_1}$ is the largest eigenvalue of $\underline{A}^H\underline{A}$ ($\underline{A}^H$ = hermitic conjugate or transpose of the complex conjugate matrix) is subordinated to the euclidian norm $\|\underline{x}\|_2$ but the Frobisher norm:

$$\|\underline{A}\|_F = \sqrt{\Sigma a_i^2\,\Sigma a_j^2} \quad \text{(A2.36)}$$

is consistent with the euclidian norm but not subordinated to it.

Finally, the following norms, which leads to faster calculations are often used:

$$\|\underline{A}\|_1 = \Sigma_i\,|a_i| \quad \text{(A2.36)}$$

and the corresponding norm for the matrix $\underline{A}$:

$$\|\underline{A}\|_1 = \max\,(\|\underline{A}_j\|_1) \quad \text{(A2.37)}$$

where $\underline{A}_j$ are the column vectors of $\underline{A}$.

Calculation of the upper bound: From the norms of the experimental errors $\|\underline{\delta y}\|$ and $\|\underline{\delta A}\|$, it is possible to calculate an upper limit to the norm of the resulting error $\|\underline{\delta x}\|$ by the use of the following relation.

If $\|\underline{I}\| = 1$ (it is true for $\|\underline{I}\|_2$), then the norm of the relative error is:

$$\frac{\|\underline{\delta x}\|}{\|\underline{x}\|} \leq \frac{\|\underline{A}\|.\|\underline{A}^{-1}\|}{1 - \|\underline{\delta A}\|.\|\underline{A}^{-1}\|} \cdot \left(\frac{\|\underline{\delta y}\|}{\|\underline{y}\|} + \frac{\|\underline{\delta A}\|}{\|\underline{A}\|} \right) \quad \text{(A2.36)}$$

The quantity:

$$\text{cond}(\underline{A}) = \|\underline{A}\|.\|\underline{A}^{-1}\| \quad \text{(A2.37)}$$

is of great importance in this calculation. It is the so-called **condition number of the matrix A** related to the used norm. This number indicates of how nearly singular is the matrix.

If the spectral norm $\|A\|_2$ is used, we get the smallest possible condition number, which is:

$$\text{cond}_2(\underline{\underline{A}}) = \|\underline{\underline{A}}\|_2 \cdot \|\underline{\underline{A}}^{-1}\|_2 = \sqrt{(\mu_1/\mu_n)} \qquad \text{(A2.38)}$$

where μ_1 and μ_n are respectively the largest and the smallest eigenvalue of $\underline{\underline{A}}^H \cdot \underline{\underline{A}}$. This number is the **spectral condition number**.

Constant absolute error

If the absolute error is constant:

$$\underline{\underline{\delta A}} = e\,\underline{\underline{1}} \text{ and } \underline{\delta y} = \delta y\,\underline{1} \qquad \text{(A2.39)}$$

where $\underline{\underline{1}}$ and $\underline{1}$ are respectively a matrix of order N and a N-component vector whose all elements are equal to 1 (They are not the identity matrix and the unit vector).

It is easy to see that:

$$\|\underline{\underline{1}}\|_2 = N \text{ and } \|\underline{1}\|_2 = \sqrt{N} \qquad \text{(A2.40)}$$

because the eigenvalues of $\underline{\underline{1}}$ are N and 0^{N-1}, and those of $\underline{\underline{1}}^H\underline{\underline{1}} = 1^2$ are N^2 and 0^{N-1}. It follows that:

$$\|\underline{\underline{\delta A}}\|_2 = e\,N \text{ and } \|\underline{\delta y}\|_2 = \sqrt{N}\,\delta y \qquad \text{(A2.41)}$$

and

$$\frac{\|\underline{\delta x}\|}{\|\underline{x}\|} \le \frac{\text{cond}_2(\underline{\underline{A}})}{1 - e\,N\,\|\underline{\underline{A}}^{-1}\|} \left(\frac{\sqrt{N}\,\delta y}{\|\underline{y}\|} + \frac{Ne}{\|\underline{\underline{A}}\|} \right) \qquad \text{(A2.42)}$$

Constant relative error: In this case, if e and ε are the constant relative errors on $\underline{\underline{A}}$ and $\underline{y}$:

$$\underline{\underline{\delta A}} = e\,\underline{\underline{A}} \text{ and } \underline{\delta y} = \varepsilon\,\underline{y} \qquad \text{(A2.43)}$$

and, from the definitions of the norms:

$$\|\underline{\underline{\delta A}}\| = e\,\|\underline{\underline{A}}\| \text{ and } \|\underline{\delta y}\| = \varepsilon\,y \qquad \text{(A2.44)}$$

and we get, for any norm satisfying $\|\underline{\underline{I}}\| = 1$:

$$\frac{\|\underline{dx}\|}{\|\underline{x}\|} \le \frac{\text{cond}(\underline{\underline{A}})}{1 - e\,\text{cond}(\underline{\underline{A}})}\,(\varepsilon + e) \qquad \text{(A2.45)}$$

assuming that $e\,\text{cond}(\underline{\underline{A}}) < 1$, that is that $\underline{\underline{A}}+\underline{\underline{dA}}$ is regular.

Example: *A measurement with two tracer gases at constant concentration in two zones gives the following results:*

	Zone 1	*Zone 2*	
Tracer concentration 1	*10*	*2.29*	*ppm*
Tracer concentration 2	*6.46*	*10*	*ppm*
Injection rate, tracer 1	*$2.65\,10^{-4}$*	*0*	*m^3/h*
Injection rate, tracer 2	*0*	*$3.6\,10^{-4}$*	*m^3/h*

From which, using the method described in Section 4.4.1 of Part III, we get the air flow rates from each zone to each other [m^3/h]:

Flow going to	*Outdoors*	*zone 1*	*Zone 2*
Flow coming from			
Outdoors	-	*11.0*	*32.6*
Zone 1	*21.4*	-	*9.7*
Zone 2	*22.2*	*20.1*	-

Let us suppose that the error on the injection rate is 5% and if the relative error on the concentration is 2%. What is the probable error on the air flows?

Using the most simple method, we get a relative error of 9 %.

Using the spectral norm, we get relative errors of 12 % for the zone 1 and 7% for the zone 2. These are upper limits easily calculated, but there is more information than the simple method, since we can see the difference in quality of the measurements between the two zones.

A 2.5. Conclusions

There are a few basic principles which should be remembered here:

- Any measurement result shall be presented together with its confidence interval.
- There are several method to estimate that interval. The method, more or less complex, should be chosen in accordance with the scope of the measurements.
- If several measurements are combined to obtain the final result, the error in that result can be much larger than the error on the measurements if the experiment is badly planned, that is if, for example, the matrix in a linear system of equation is ill-conditioned.

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Note on the demonstration of the relation:

$$\frac{\partial \alpha_{ij}}{\partial a_{kl}} = - \alpha_{ik} \alpha_{lj}$$

where a_{kl} are the coefficients of a matrix $\underline{\underline{A}}$ and α_{ij} are those of the inverse matrix $\underline{\underline{A}}^{-1}$. By definition of the inverse of a matrix:

$$\sum_n \alpha_{in} a_{nm} = \delta_{im} \qquad \text{with} \qquad \delta_{im} = 1 \quad \text{if} \quad i = m, \quad \text{and 0 otherwise.}$$

hence any derivative of that expression is zero. For example:

$$\frac{\partial}{\partial a_{kl}} \sum_n \alpha_{in} a_{nm} = 0$$

or

$$\sum_n \left[\frac{\partial \alpha_{in}}{\partial a_{kl}} a_{nm} + \alpha_{in} \frac{\partial a_{nm}}{\partial a_{kl}} \right] = 0$$

Multiplying at the right by α_{mj} and summing over m gives:

$$\sum_m \sum_n \frac{\partial \alpha_{in}}{\partial a_{kl}} a_{nm} \alpha_{mj} + \sum_m \sum_n \alpha_{in} \frac{\partial a_{nm}}{\partial a_{kl}} \alpha_{mj} = 0$$

hence:

$$\sum_m \sum_n \frac{\partial \alpha_{in}}{\partial a_{kl}} \delta_{nj} + \sum_m \sum_n \alpha_{in} \delta_{nk} \delta_{ml} \alpha_{mj} = 0$$

or, finally

$$\frac{\partial \alpha_{ij}}{\partial a_{kl}} + \alpha_{ik} \alpha_{lj} = 0$$

Appendix 3. Identification Methods

A 3.1. Introduction

The rough results of a measurement seldom give directly the expected physical quantities. The figures obtained from the results shall be treated in order to get the desired data.

This treatment is performed using a model of the reality. A simple example is the measure of the air flow through an orifice plate (see part II, § 3.2.5). The air flow rate Q is related to the pressure difference Δp across the orifice by:

$$Q = K\sqrt{\Delta p} \qquad \text{(A 3.1)}$$

where K is a constant depending on the geometry of the orifice. This is a part of the model used, since Δp is not obtained directly: it is calculated with another model from the measurement of either a water column height or a voltage delivered by an electronic manometer.

This example shows a simple model, which can be solved to get directly the desired quantity. Some models are too complicated to be solved, the equation contains the unknowns intrinsically. For example, the energy requirement of a building submitted to measured meteorological conditions depends on the areas of the various envelope elements and their thermal transmittance, on the thermal mass of the building, on the windows areas, transmissivity and shadows, on the air change rate and the air volume, etc. From a model of the energy requirement of the building, it is theoretically possible to obtain all these characteristics from the measurement of the energy used under various meteorological conditions. These techniques are called "identification techniques", since the various coefficients of the model are identified on the basis of measurements.

Of course, it is never possible to obtain exact values, and such identified parameters are always estimates, which should be given with their confidence interval.

There are several identification techniques. Only techniques which may be useful for measurements related to air leakage and air flows are presented below. The basis of the presented methods can be found in the literature, so only the final formula are presented here.

A 3.2. Linear Least Square Fit Technique

A 3.2.1. Regression of the First Kind

The problem is the following: given N pairs of data (x,y), find the straight line:

$$y = a + b\,x \qquad \text{(A3.2)}$$

fitting these points at the best. That means that the coefficients a and b should be such that the sum of the "distances" of the measured points to the line is minimum.

The regression of the first kind assumes that the abscissae are well known and that the distribution of the ordinates around the regression line is gaussian with a constant standard deviation. This method is very commonly used but it should be emphasized that the above hypothesis are **often not verified in practice**, mainly when the values of x are measured estimates.

The regression line of the first kind minimizes the sum of the square of the residual ordinates :

$$SSR_y = \sum_{i=1}^{N} [y_i - (a + b\,x_i)]^2 \qquad \text{(A 3.3)}$$

Its coefficients can be calculated using the following relationships. First compute

- the estimates of the averages:

$$\langle x \rangle = \frac{1}{N} \sum_{i=1}^{N} x_i \qquad \text{(A 3.4)}$$

$$\langle y \rangle = \frac{1}{N} \sum_{i=1}^{N} y_i$$

- and the estimates of the variances:

$$s_x^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \langle x \rangle)^2 \qquad \text{(A 3.5)}$$

$$s_y^2 = \frac{1}{N-1} \sum_{i=1}^{N} (y_i - \langle y \rangle)^2$$

$$s_{xy} = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \langle x \rangle)(y_i - \langle y \rangle)$$

Then the best estimates of the coefficients a and b, according the above hypotheses, are:

$$b = \frac{s_{xy}}{s_x^2} \qquad \text{(A 3.6)}$$

$$a = \langle y \rangle - b \langle x \rangle \qquad \text{(A 3.7)}$$

The slope given by equation (A 3.6) is valid if the x_i are exactly known, and the minimized distance is the vertical distance between the measured points and the regression line.

A 3.2.2. Regression of the Second Kind

When there are uncertainties in both axes, there is no reason to emphasize the x axis, and the same procedure can be followed commuting the roles of x and y. Generally another regression line is obtained, which is given by:

$$y' = a' + b' x \qquad \text{(A 3.8)}$$

with another pair of coefficients

$$b' = \frac{s_y^2}{s_{xy}} \qquad \text{(A 3.9)}$$

$$a' = \langle y \rangle - b' \langle x \rangle \qquad \text{(A 3.10)}$$

This regression line minimizes the sum of the square of the residual abscissae (figure A 3.1):

$$SSR_x = \sum_{i=1}^{N} \left\{ x_i - \frac{y' - a'}{b'} \right\}^2 \qquad \text{(A 3.11)}$$

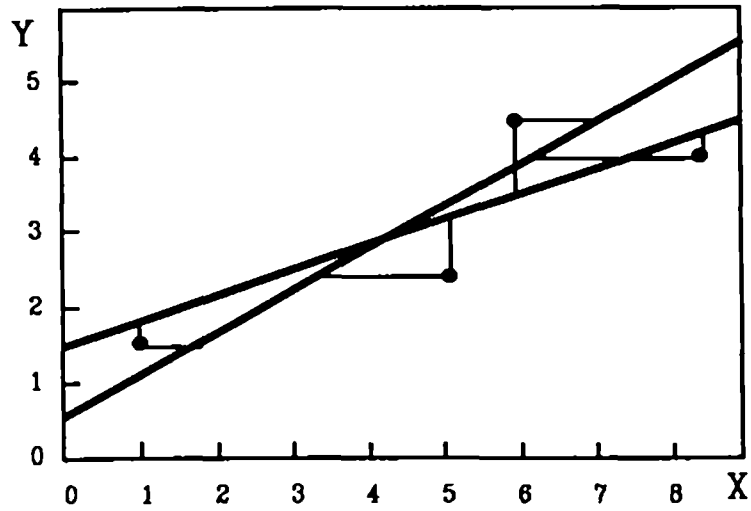

Figure A 3.1: Regressions of the first and the second kind.

If the two lines are close to each other or, in other words, if:

$$b' \approx b \quad \text{and therefore} \quad a' \approx a \tag{A 3.12}$$

then it can be said that there is a good correlation between the two physical quantities x and y. The correlation coefficient defined by:

$$R = \frac{s_{xy}}{s_x s_y} \qquad \text{hence} \qquad R^2 = \left| \frac{b}{b'} \right| \tag{A 3.13}$$

is a measure of the inter-dependance of x and y. **It is not a measure of the goodness of the fit**, or of the accuracy of the estimates of the coefficients, since $|R| = 1$ for any fit based on two sets of points. The estimates of the errors on a and b are calculated in paragraph A 3.2.4.

A 3.2.3. Orthogonal Regression

If the two regressions of the second kind are calculated and different results are obtained, the problem is to choose the coefficients: which pair is the closest to the reality? Since each pair of coefficients are obtained assuming that one variable is exactly known, it is likely that the best set is none of them but lies in between. But where?

There are several answers to that question, none of them being really satisfactory. One cooking recipe is to take an average slope:

$$\langle b \rangle = (b + b')/2 \tag{A 3.14}$$

or a weighted average slope:

$$\langle b \rangle = (\varepsilon_y b + \varepsilon_x b')/2 \tag{A 3.15}$$

where ε_y and ε_x are the experimental errors on y and x respectively and deduce a corresponding value of a using (A 3.7). This recipe does not show clearly which quantity is minimized by the fit.

Another more physical way is the so-called "orthogonal" regression (Figure A 3.2). It minimizes the real (orthogonal) distance between the measured points and the regression line drawn with the scales on the axes inversely proportional to the experimental errors, that is with the variables:

$$Y = y_i / \varepsilon_y \quad \text{and} \quad X = x_i / \varepsilon_x \tag{A 3.16}$$

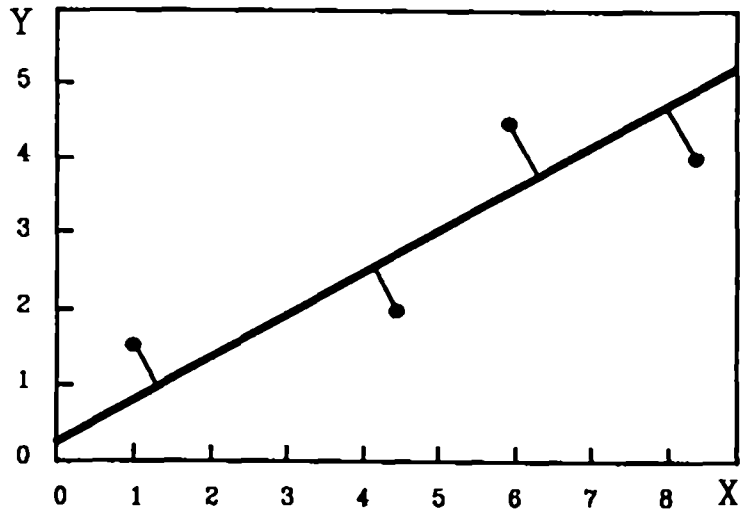

***Figure A 3.2**: Orthogonal regression.*

Writing the regression line with these coordinates:

$$Y = A + B X \tag{A 3.17}$$

the minimized residual is:

$$SSR_{\wedge} = \sum_{i=1}^{N} \frac{(Y_i - B X_i - A)^2}{B^2 + 1} \qquad \text{(A 3.18)}$$

The slope in original (x, y) coordinates is given by the following relations. Let us define:

$$\Delta b = \frac{s_y^2 - s_x^2}{2 s_{xy}} \qquad \text{(A 3.19)}$$

If σ_x and σ_y are respectively the estimated standard deviations of the abscissae x_i and ordinates y_i, the slope is given by:

$$b_{\perp} = \frac{\sigma_y}{\sigma_x} \left\{ \Delta b \pm \sqrt{\Delta b^2 + 1} \right\} \qquad \text{(A 3.20)}$$

Between the two possibilities, the sign of $b_{\perp}$ must be chosen equal to the sign of b given by equation (A 3.6). This sign is always positive in pressurization tests. The coefficients a is obtained with the relation (A 3.7).

A 3.2.4. Linearizeable Fits

Several non-linear functions can be linearized by a change in the variables. The table A 3.1 shows some of these functions, together with the convenient changes.

#	Original Function	Modified function Y = A + B X					Limits
1	$y = a\,x^b$	$\ln(y)$	=	$\ln(a)$	+ b	$\ln(x)$	$x>0$ & $y>0$
2	$y = a\exp(bx)$	$\ln(y)$	=	$\ln(a)$	+ b	x	$y>0$
3	$y = \exp(ax^b)$	$\ln[\ln(y)]$	=	$\ln(a)$	+ b	$\ln(x)$	$y>0$
4	$y = a\,x + b\,x^2$	y/x	=	a	+ b	x	$x \neq 0$
5	$y = (a + b\,x)^n$	$y^{1/n}$	=	a	+ b	x	$y \neq 0$
6	$y = \ln(a + b\,x)^n$	$\exp(y)$	=	a	+ b	x	$(a + bx) > 0$
7	$y = f(a + b\,x)$	$f^{-1}(y)$	=	a	+ b	x	f^{-1} exists

Table A 3.1: Some functions which can be easily modified for a linear least square fit. Functions 1 and 4 are used to model the air leakage characteristics and function 2 models the tracer gas concentration decay.

A 3.2.5. Errors on the Coefficients

The variances on the linear coefficients of the regression of the first kind are usually estimated using the following relations, which assume that the dispersion around the line is gaussian with a constant standard deviation and is the result of the measurement errors:

$$s_b = \frac{1}{s_x}\left[\frac{s_y^2 - b\,s_{xy}}{N-2}\right]^{1/2}$$

$$s_a = s_b \left[\frac{\Sigma x_i^2}{N}\right]^{1/2} \qquad \text{(A 3.21)}$$

If $T(P,\nu)$ is the significance limit of the two-sided Student distribution for a probability P on ν events, then the confidence levels on the coefficients are:

$$I_a = s_a\,T(P, N\text{-}2) \qquad \text{(A 3.22)}$$

$$I_b = s_b\,T(P, N\text{-}2) \qquad \text{(A 3.23)}$$

This means that with a probability P the coefficient a lies in the interval $[a - I_a, a + I_a]$ and the same for b.

The estimate of the variance around the regression line at the value x is:

$$s_y(x) = s_b \sqrt{(N-1)\, s_x^2/N + (x-\langle x\rangle)^2} \qquad \text{(A3.24)}$$

and the confidence interval in the estimate of y using the regression line for any x is:

$$I_y(x) = s_y(x)\, T(P, N-2) \qquad \text{(A3.25)}$$

The values of the two-sided Student distribution are given in Appendix 2. The relation A 3.21 may be used to obtain the confidence intervals for a' and b' in the second kind regression if the roles of x and y are permuted.

A 3.3. Bayesian Identification

A 3.3.1. Introduction

As it was said in § A 3.2.3, the usual regression techniques for the identification of the coefficients can strictly be used only when one of the variable is well controlled. In this case only, the relations given in § A 3.2.4 can be used to get a good estimate of the confidence intervals of the obtained coefficients.

When there are uncertainties on both axes, like for example in pressurization tests, these methods are not strictly valid, since they do not give any information on the relation between the two coefficients and their uncertainties. If several measurements of the same leak are performed, several pairs of coefficients C and n for the relation:

$$Q = C\, \Delta p^n \qquad \text{(A 3.26)}$$

will be obtained, and a correlation between C and n will be found: the larger C values correspond to the smaller n and vice-versa. A good identification technique should give the most likely couple of coefficients together with the probability density f(a,b). Such technique exist *[Tarantola, 1987]* and is summarized below.

A 3.3.2. Identification of the Model Parameters

Let put in a vector $\underline{z}$ as well the measured data as the model parameters, which have to be determined and assume that this vector is a random variable with a normal distribution in the k-fold space (k = number of parameters and data):

$$f(\underline{z}) = \text{Cst} \exp[-(\underline{z} - \underline{z}_p)^T\, \underline{\underline{C}}_z^{-1}\, (\underline{z} - \underline{z}_p)/2] \qquad \text{(A 3.27)}$$

where:

$\underline{z}_p$ is the "a priori" vector $\underline{z}$ containing the measured values and reasonable estimates of the parameters to be identified

$\underline{\underline{C}}_z$ is the covariance matrix between the elements of $\underline{z}$. Its diagonal elements are the variances of the measured quantities and a priori estimated variances or the parameters. These latter variances are generally large, since these parameters are generally not known before the measurements.

The components of the vector $\underline{z}$ are linked by a model, that is by equations which can be written:

$$\underline{\rho}(\underline{z}) = \underline{0} \qquad \text{(A 3.28)}$$

For example, if a linear relationship is assumed between two measured variables x and y, the set of equations:

$$y_i = a + b\, x_i \qquad \text{(A 3.29)}$$

can be written in a matrix form:

$$\begin{pmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ 1 & x_n & y_n \end{pmatrix} \begin{pmatrix} a \\ b \\ -1 \end{pmatrix} = \underline{0} \qquad \text{(A 3.30)}$$

Generally, the proposed model is not exact and it may be assumed that it has a normal distribution:

$$g(\underline{z}) = Cst \exp[-\rho(\underline{z})^T \underline{\underline{C}}_T^{-1} \rho(\underline{z})/2] \quad (A\ 3.31)$$

where $\underline{\underline{C}}_T$ is the covariance matrix of the model. If the model is exact, this distribution is a Dirac distribution:

$$g(\underline{z}) = \delta[\rho(\underline{z})] \quad (A\ 3.32)$$

Combining the prior knowledge contained in the distribution $f(\underline{z})$ with the model described with the distribution $g(\underline{z})$ gives a new distribution containing the "a posterior" information. This new distribution is (see reference *[Tarantola, 1987]* for the detailed development):

$$\sigma(\underline{z}) = Cst \exp[-\frac{1}{2} \{\rho(\underline{z})^T \underline{\underline{C}}_T^{-1} \rho(\underline{z}) + (\underline{z} - \underline{z}_p)^T \underline{\underline{C}}_z^{-1} (\underline{z} - \underline{z}_p)\}] \quad (A\ 3.33)$$

From this distribution, the $\underline{z}$ vector presenting the maximum likelihood can be found, it is the vector which minimizes the exponent:

$$\underline{z}_s = \underline{z} \text{ for } [\rho(\underline{z})^T \underline{\underline{C}}_T^{-1} \rho(\underline{z}) + (\underline{z} - \underline{z}_p)^T \underline{\underline{C}}_z^{-1} (\underline{z} - \underline{z}_p)] \text{ minimum} \quad (A\ 3.34)$$

This most probable vector contains the identified model parameters and the most probable values of the measured quantities. Practically, this vector is found using numerical methods looking for the minimum of the exponent given in equation A 3.34. References on such methods are quoted in Section A 3.4.

A 3.3.3. Error Analysis

This method allows to obtain a posterior estimate $\underline{\underline{C}}_z^i$ of the covariance matrix of the distribution $\sigma(\underline{z})$. For that purpose, the model $\rho(\underline{z})$ is linearized around the most probable vector $\underline{z}_s$. The posterior covariance matrix is then:

$$\underline{\underline{C}}_z^i = (\underline{\underline{F}}_s^T \underline{\underline{C}}_T^{-1} \underline{\underline{F}}_s + \underline{\underline{C}}_z^{-1})^{-1} = \underline{\underline{C}}_z - \underline{\underline{C}}_z \underline{\underline{F}}_s^T (\underline{\underline{F}}_s \underline{\underline{C}}_z \underline{\underline{F}}_s^T + \underline{\underline{C}}_T)^{-1} \underline{\underline{F}}_s \underline{\underline{C}}_z \quad (A\ 3.35)$$

where $\underline{\underline{F}}_s$ is a matrix having the dimension N × M, with M = N n + n + N, N being the number of measurements and n the number of parameters to be identified. $\underline{\underline{F}}_s$ contains the derivatives of the model $\rho(\underline{z})$ evaluated at the point $\underline{z}_s$:

$$\underline{\underline{F}}_s = \begin{pmatrix} \frac{\partial \rho_1}{\partial z_1} & \cdots & \frac{\partial \rho_1}{\partial z_M} \\ \cdots & \cdots & \cdots \\ \frac{\partial \rho_N}{\partial z_1} & \cdots & \frac{\partial \rho_N}{\partial z_M} \end{pmatrix}_{\underline{z}_s} \quad (A\ 3.36)$$

A 3.3.4. Case of a Linear Model

If the theoretical model is linear, the relation (A 3.28) is replaced by:

$$\underline{\underline{F}}\,\underline{z} = \underline{0} \quad (A\ 3.37)$$

where $\underline{\underline{F}}$ is a linear operator acting from a total space of parameters into a space of residuals. Applying the method described above, the most probable vector $\underline{z}$ is given by (see [A3.6] p 78):

$$\underline{z}_s = \underline{z}_p - \{\underline{\underline{F}}^T \underline{\underline{C}}_T^{-1} \underline{\underline{F}} + \underline{\underline{C}}_z^{-1}\}^{-1} \underline{\underline{F}}^T \underline{\underline{C}}_T^{-1} \underline{\underline{F}}\,\underline{z}_p \quad (A\ 3.38)$$

$$= \underline{z}_p - \underline{\underline{C}}_z \underline{\underline{F}}^T \{\underline{\underline{F}} \underline{\underline{C}}_z \underline{\underline{F}}^T + \underline{\underline{C}}_T\}^{-1} \underline{\underline{F}}\,\underline{z}_p$$

The posterior estimate $\underline{\underline{C}}_z^i$ of the covariance matrix is then:

$$\underline{\underline{C}}_z^i = \underline{\underline{C}}_z - \underline{\underline{C}}_z \underline{\underline{F}}^T (\underline{\underline{F}} \underline{\underline{C}}_z \underline{\underline{F}}^T + \underline{\underline{C}}_T^{-1})^{-1} \underline{\underline{F}} \underline{\underline{C}}_z \quad (A\ 3.39)$$

Note that a model such as the linear fit

$$y = a + b\,x$$

where x and y are measured and a and b must be identified is **not** a linear model, since it contains the product b x of two components of $\underline{z}$.

A 3.4 References

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Nelder, A. and Mead, R [1965]: A Simplex Method for Function Minimization. *J. Comput. J. 7, pp 308-313, 1965.*

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Appendix 4. Example of Multizone Pressurization in a Realistic Case

A 4.1. Introduction

Buildings are very often made of rooms connected to a corridor or staircase, all these zones being connected to the outdoor air. To measure the corresponding air leakage distribution, two experimental plans can be defined, which leads to different confidences in the results depending widely on the situation of the measured leaks.

After a description of the representation of each experimental plan, the estimators of the leakage parameters will be exhibited and discussed.

It is important to remember that some experimental plans may not be possible for some buildings because of the limited range of the flow meters and expected disparity of air tightness.

Hereafter, "measure" will be referred to as a series of pressure differences and flow measurements which can be fitted on a relation such as :

$$Q = f(\Delta p) \qquad \text{(A 4.1)}$$

Figure A 4.1 presents the typical situation for a room with three neighbors measured with a two-fans technique. The flows will be all along this section referred to in the same way.

Q_e : flow between the given room and outside
Q_2, Q_4 : flow between the given room and a lateral neighbor
Q_3 : flow between the given room and the hall
Q_m : measured flow

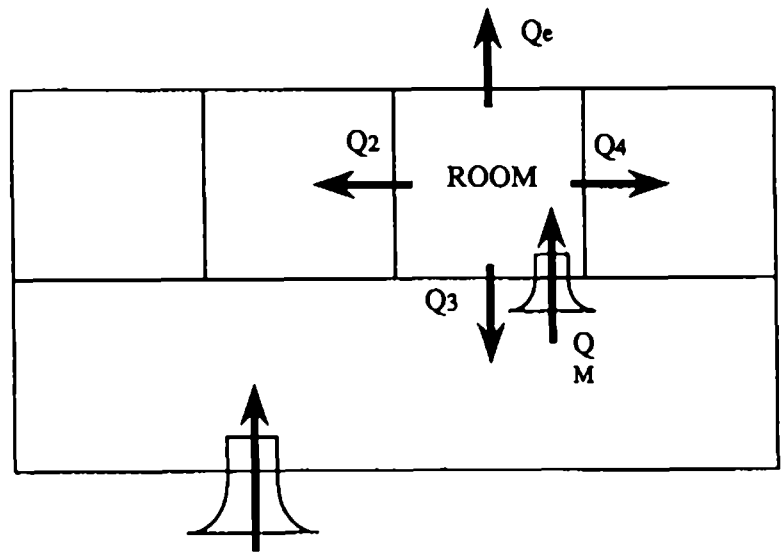


Figure A 4.1: The flow during a pressurization test.

Figure A 4.2 allows one to define the use of the terms *"pressure ring"*, *"room"* and *"outside"* for a better understanding.

The two experimental plans which can be used to measure the leakage distribution in this case are the so-called "deduction method" and "guard zone method". It is shown below how to use these methods for measuring the leakage distribution in buildings.

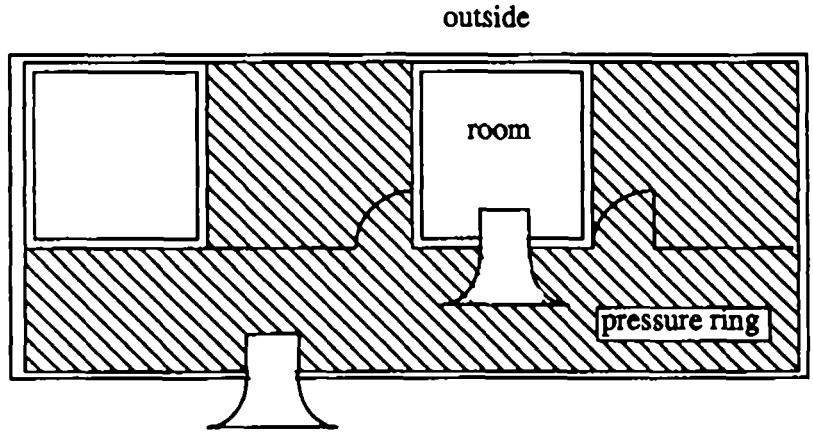


Figure A 4.2: Measurement situation

A 4.2. Deduction Method

The deduction method (also called "progressive equalization") consists on varying the pressure p_m in the **pressure ring**, keeping a constant pressure p_r in the **room** as schematized in figure A 4.3 so that :

$$p_r - p_m = \Delta p \qquad \text{(A 4.2)}$$

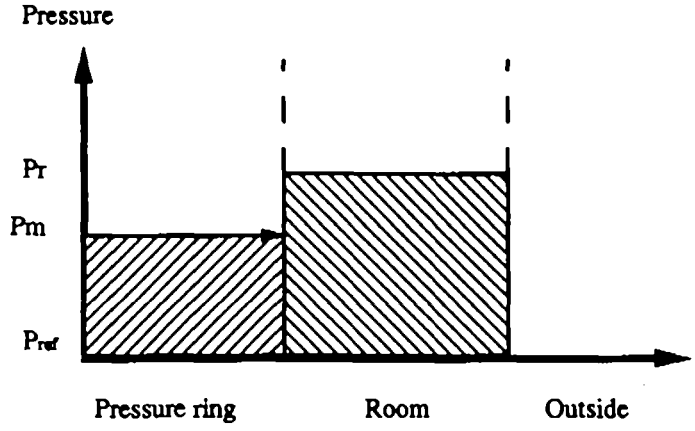


Figure A 4.3: Pressure level in pressurization test with deduction method.

By using this method it is possible to measure all the flows Q_e, Q_2, Q_3, Q_4 directly or indirectly, as described below.

A 4.2.1.Room-to-hall Flow Estimation

The flow $Q_3(\Delta p)$ is available directly from two measurements in the same experiment: by opening windows and closing doors in adjacent rooms, the pressure ring is limited to the hall . The experiment is shown in figure A 4.4.
The estimator of $Q_3(\Delta p)$ is then :

$$Q_3(\Delta p) = Q_{D1}(p_r - p_m) - Q_{D1}(p_r - p_r) = Q_{D1}(\Delta p) - Q_{D1}(0) \qquad \text{(A 4.3)}$$

Where p_r is the constant pressure in the room and $Q_{D1}(\Delta p)$ is the result of the experiment $D1$ at the pressure difference Δp between the pressure ring and the room.

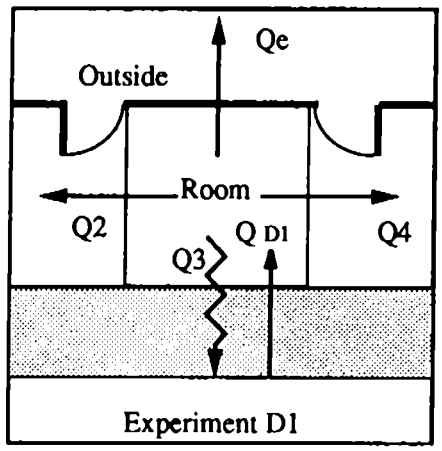


Figure A 4.4: Experiment to obtain $Q_3(\Delta p)$ (The zig-zag arrow represents the step-by-step varying pressure).

A 4.2.2.Lateral Flow Estimation

It is necessary to perform two experiments, $D1$ and $D2$ to obtain the lateral flow Q_2 or Q_4. The plan adapted for the measurement of $Q_2(\Delta p)$ is shown in the figure A 4.5

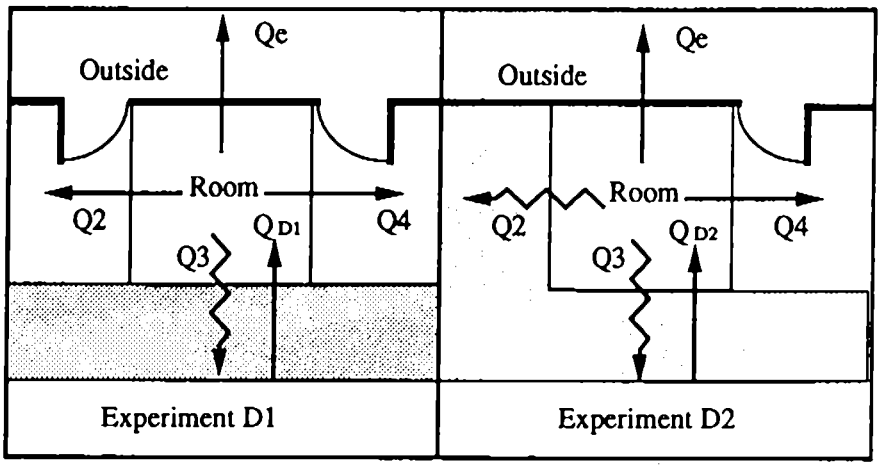


Figure A 4.5: The two experiments necessary to obtain a lateral flow with the deduction method.

The estimator of $Q_2(\Delta p)$ is then :

$$Q_2(\Delta p) = Q_{D2}(\Delta p) - Q_{D2}(0) - Q_{D1}(\Delta p) + Q_{D1}(0) \qquad \text{(A 4.4)}$$

A 4.2.3.External Flow Estimation

This flow $Q_e(\Delta p)$ also needs two different experiments (figure A 4.6). In the first one, $D3$, the pressure ring is constituted by all the adjacent rooms and the second one, T, consists of pressuring only the room, keeping the hall and the adjacent rooms at the outside pressure by opening doors and windows.

The estimator of Q_e is then :

$$Q_e(\Delta p) = Q_T(\Delta p) - [Q_{D3}(\Delta p) - Q_{D3}(0)] \qquad \text{(A 4.5)}$$

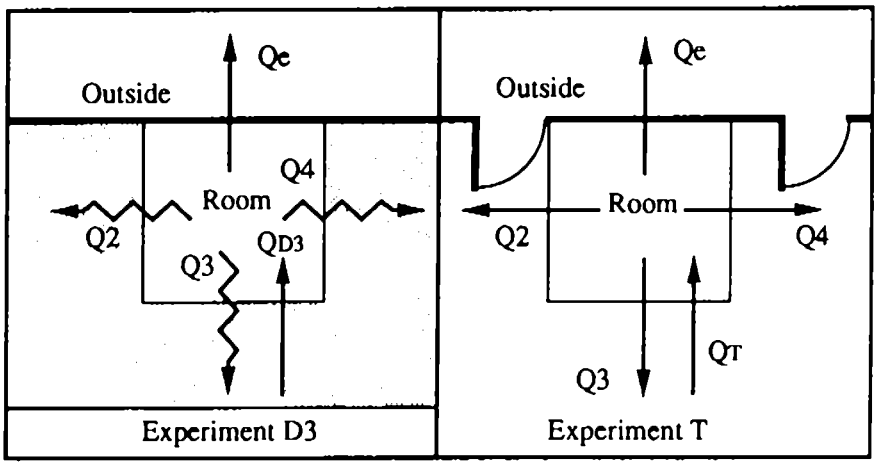


Figure A 4.6: The two experiments necessary to obtain the external flow Q_e using the deduction method.

A 4.2.4.Estimation of the Errors Occurring in Flows $Q_i(Dp)$

Now let us look out the error analysis through the deduction process. The preceding items have shown how to obtain the flows $Q_i(\Delta p)$ of the leak i at the pressure difference Δp by summing or subtracting flows Q_{Di} from at most 4 measurements at pressure difference Δp or Δp_r.

At this point we are interested to obtain a confidence limit for the flows Q_i, which can be estimated by:

$$Q_i = Q_{i,mes} \pm T(P,\nu)\, s(Q_i) \qquad \text{(A 4.6)}$$

where $Q_{i,mes}$ is the measurement result, $T(P,\nu)$ the Student coefficient with probability P and ν degree of freedom, and $s(Q_i)$ the estimate of the standard deviation of the result.

The theory of error estimation gives the following estimate of $s(Q_i)$ as function of the deviation of its parameters.

$$s^2(Q_i) = \Sigma \left[\frac{\partial Q_{Di}}{\partial \Delta p_j} \right]^2 s^2(\Delta p_j) + \Sigma\, s_Q + \Sigma\, \delta q_i^2 \qquad \text{(A 4.7)}$$

where s_Q is the own standard deviation of the volumetric measurement obtained during the calibration and given the flow meter precision (5%), δq_i is an additional flow through the conductance i produced by slight pressure differences through conductances where this Δp should be zero.

Applying this at flow Q_3 and taking into account that

$$Q_{3,mes} = Q_{D1}(\Delta p) - Q_{D1}(0) \qquad \text{(A 4.3 again)}$$

we have :

$$s^2(Q_3) = s^2(Q_{D1}(\Delta p)) + s^2(Q_{D1}(0)) + \Sigma\, s_{D2} + \Sigma\, \delta q_i^2 \qquad \text{(A 4.8)}$$

The standard deviation of the zero pressure difference being $s_{\Delta po}$, we have:

$$\delta q_i = C_i\, (s_{po})^{n_i} \qquad \text{(A 4.9)}$$

As $Q_{D1}(\Delta p)$ is the sum of the flows through several conductances i, its standard deviation is given by :

$$s^2(Q_{D1}(\Delta p)) = \Sigma \left[\frac{\partial Q_i}{\partial \Delta p_j} \right]^2 s^2(\Delta p_j) = \Sigma\, n_i^2\, (C_i\, \Delta p_i^{n_i})^2\, (s_{\Delta pi}/\Delta p_i)^2 \qquad \text{(A 4.10)}$$

and finally

$$s^2(Q_{D1}(\Delta p)) = \sum_{i\neq 3} n_i^2 (C_i \Delta p_i^{n_i})^2 (s_{\Delta pr}/\Delta p_r)^2 + n_3^2 (C_3 \Delta p_3^{n_3})^2 (s_{\Delta p}/\Delta p)^2 \qquad \text{(A 4.11)}$$

So, $s^2(Q_3)$ can be computed according to (A 4.8). Similar calculations are done for the other flows. Table A 4.1 shows the relative error :

$$E_{D,\Delta p}(Qi) = s_p(Q_i)/Q_i \qquad \text{A 4.12}$$

caused by pressure instabilities and assuming a constant exponent n for every element, while table A 4.2 shows the part $s_Q(Q_i)/Q_i$ of the relative error coming from the uncertainties in flow measurements. The total error is the geometrical average of these two elements:

$$\frac{s(Q)}{Q} = \sqrt{[E_{D,\Delta p}(Qi)]^2 + [E_{D,Qm}(Qi)]^2} \qquad \text{A 4.13}$$

$$E_{D,\Delta p}(Q_e) = \left\{ n^2 \frac{s_{\Delta p}^2}{\Delta p^2} \left[2 \sum_{i=2}^{4} \frac{C_i^2}{C_e^2} + 2\left(\frac{\Delta p_r}{\Delta p}\right)^{2n} + 1 \right] + \left(\frac{s_{\Delta po}}{\Delta p}\right)^{2n} \sum_{i=2}^{4} \frac{C_i^2}{C_e^2} \right\}^{1/2}$$

$$E_{D,\Delta p}(Q_2) = \left\{ n^2 \frac{s_{\Delta p}^2}{\Delta p^2} \left[2 \frac{C_3^2}{C_2^2} + \left(\frac{\Delta p_r}{\Delta p}\right)^{2n} \left[4 \frac{C_e^2 + C_4^2}{C_2^2} + 2 \right] + 1 \right] + \left(\frac{s_{\Delta po}}{\Delta p}\right)^{2n} \left[2 \frac{C_3^2}{C_2^2} + 1 \right] \right\}^{1/2}$$

$$E_{D,\Delta p}(Q_3) = \left\{ n^2 \frac{s_{\Delta p}^2}{\Delta p^2} \left[2 \left(\frac{\Delta p_r}{\Delta p}\right)^{2n} \sum_{i=1}^{4} \frac{C_i^2}{C_3^2} + 1 \right] + \left(\frac{s_{\Delta po}}{\Delta p}\right)^{2n} \right\}^{1/2}$$

$E_{D,\Delta p}(Q_4)$: like $E_{D,\Delta p}(Q_2)$ but permuting C_2 and C_4

Table A 4.1: Relative errors $s_{\Delta p}/Q_i$ occurring in the deduction method for flow Q_i and caused by the pressure instabilities,being assumed: a perfect flow measurement, a constant relative error $s_{\Delta p}/\Delta p$ on the pressure differences Δp_i and Δp_r, a constant exponent n and a standard deviation $s_{\Delta po}$ for zero pressure differences.

$$E_{D,Qm}(Q_e) = E(Q_m)\left\{ 2\left(\frac{\Delta p_r}{\Delta p}\right)^{2n} + 2\left[\left(\frac{\Delta p_r}{\Delta p}\right)^{n} + 1\right] \sum_{i=2}^{4} \frac{C_i}{C_e} + 2\left[\sum_{i=2}^{4} \frac{C_i}{C_e}\right]^2 + 1 \right\}^{1/2}$$

$$E_{D,Qm}(Q_2) = E(Q_m)\left\{ \left(\frac{\Delta p_r}{\Delta p}\right)^{2n} [4\chi^2 + 4\chi + 2] + \left(\frac{\Delta p_r}{\Delta p}\right)^{n} [2\chi(1 + 2\zeta) + 2\zeta] + 2\zeta^2 + 2\zeta + 1 \right\}^{1/2}$$

where $\chi = (C_e + C_4)/C_2$ and $\zeta = C_3/C_2$

$$E_{D,Qm}(Q_3) = E(Q_m)\left\{ 2\left(\frac{\Delta p_r}{\Delta p}\right)^{2n} \left(\sum_{i\neq 3} \frac{C_i}{C_3}\right)^2 + 2\left(\frac{\Delta p_r}{\Delta p}\right)^{n} \left(\sum_{i\neq 3} \frac{C_i}{C_3}\right) + 1 \right\}^{1/2}$$

$E_{D,Qm}(Q_4)$: like $E_{D,Qm}(Q_2)$ but permuting C_2 and C_4

Table A 4.2: Relative errors s_Q/Q_i occurring in the deduction method for flow Q_i and caused by errors in the flow measurements. A constant exponent n is assumed. In tables A 4.2 and A 4.4, $E(Q_m) = s_{Qm}/Q_m$

More synthetically it should be understood that the desired flow, Q_i, is obtained by difference between large flows, which may have acceptable absolute errors, but this error will be large when compared to the small difference. The disadvantage of this method is the number of flow measurements necessary to obtain some individual flows.

It is also easily understandable that the tightest the measured element is, the worst will be the confidence in the result.

A 4.3 Guard Zone Technique

In the guard zone method the pressure in the **pressure ring** (guarding zone) is always the same as that of the **room** (guarded zone) as illustrated in figure A 4.7.

In the experimental schemes the guarded walls are indicated as hatched zones as in figure A 4.8.

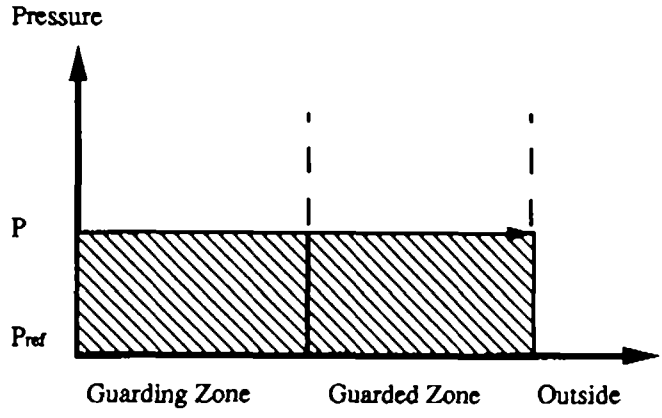


Figure A 4.7: Pressure levels in pressurization test with guard zone method.

A 4.3.1.External Flow Estimation

External flow $Q_e(\Delta p)$ is available in one experiment G_1 presented in figure A 4.8.

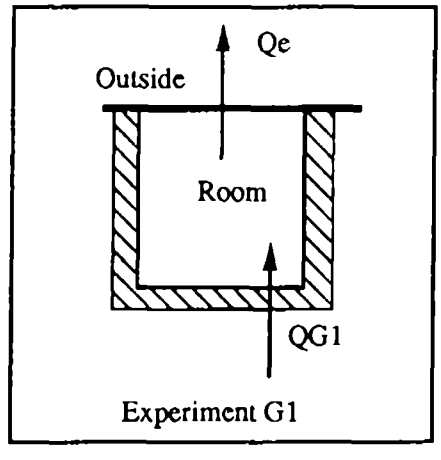


Figure A 4.8: The experiment to obtain the external flow Q_e using the guard zone method.

The estimator is the simplest one :

$$Q_e(\Delta p) = Q_{G1}(\Delta p) \qquad \text{(A 4.14)}$$

A 4.3.2.Lateral Flow Estimation

Using the same type of experimentation plan as previously, e.g. changing the guarding zone by opening windows and closing doors, it is possible to measure the lateral Q_2 or Q_4 (figure A 4.9).

$Q_2(\Delta p)$ or $Q_4(\Delta p)$ is given by :

$$Q_2(\Delta p) = Q_{G2}(\Delta p) - Q_{G1}(\Delta p) \qquad \text{(A 4.15)}$$

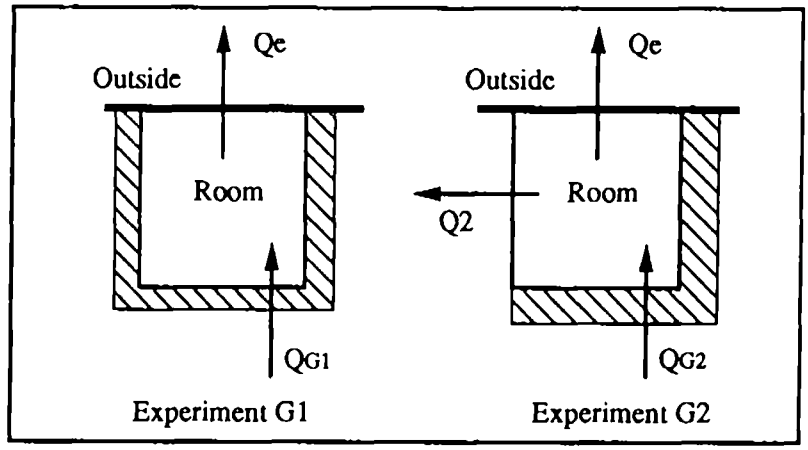


Figure A 4.9: The experiments to obtain the lateral flow Q_2 (Δp) using the guard zone method.

A 4.3.3.Room to Hall Flow Estimation

The plan presented in figure A 4.4 give the following estimator for $Q_3(\Delta p)$

$$Q_3(\Delta p) = Q_T(\Delta p) - Q_{G3}(\Delta p) \qquad \text{(A 4.16)}$$

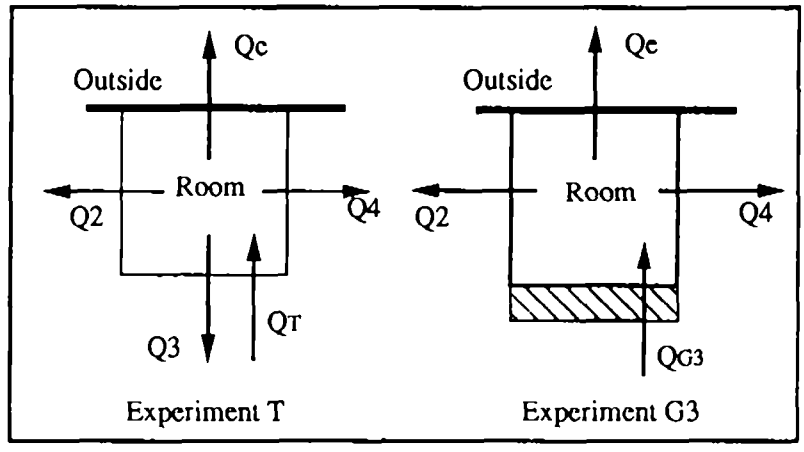


Figure A 4.10: The experiments to obtain the flow Q_3 (Δp) using the guard zone method.

A 4.3.4.Estimation of the Errors Occurring in Flows $Q_i(\Delta p)$

Using the same hypothesis as previously for the deduction method, we obtain for the guard zone method the relative errors listed in table A 4.3 and A 4.4.

In this method the principal source of error is the inaccuracy in the zero pressure difference between the guarded zone and the guarding zone.

$$E_{G,\Delta p}(Q_e) = \left\{ n^2 \left(\frac{s_{\Delta p}}{\Delta p}\right)^2 + \left(\frac{s_{\Delta po}}{\Delta p}\right)^{2n} \left(\frac{\Sigma_{i \neq e} C_i^2}{C_e^2}\right) \right\}^{1/2}$$

$$E_{G,\Delta p}(Q_2) = \left\{ n^2 \left(\frac{s_{\Delta p}}{\Delta p}\right)^2 \left(2 \left(\frac{C_e}{C_2}\right)^2 + 1\right) + \left(\frac{s_{\Delta po}}{\Delta p}\right)^{2n} \left(2 \frac{C_3^2 + C_4^2}{C_2^2} + 1\right) \right\}^{1/2}$$

$$E_{G,\Delta p}(Q_3) = \left\{ n^2 \left(\frac{s_{\Delta p}}{\Delta p}\right)^2 \left(\frac{2}{C_3} \sum_{i=1}^{4} C_i^2 - 1\right) + \left(\frac{s_{\Delta po}}{\Delta p}\right)^{2n} \right\}^{1/2}$$

$E_{G,\Delta p}(Q_4)$: like $E_{G,\Delta p}(Q_2)$ but permuting C_2 and C_4

Table A 4.3: Relative errors occurring in the guard zone method for the estimation of the flow $Q_i(\Delta_p)$, being assumed a constant relative error $s_{\Delta p}/\Delta p$ on the pressure difference Δp_n and Δp_r, a constant exponent n for every elements and a standard deviation $s_{\Delta po}$ for the pressure difference $\Delta p = 0$, s_m comes from the flow meter inaccuracy.

$$E_{G,Qm}(Q_e) = E(Q_m)$$

$$E_{G,Qm}(Q_2) = E(Q_m) \left\{ 2 \left(\frac{C_e}{C_2}\right)^2 + 2 \frac{C_e}{C_2} + 1 \right\}^{1/2}$$

$$E_{G,Qm}(Q_3) = E(Q_m) \left\{ 2 \left(\sum_{i=1}^{4} \frac{C_i}{C_3} \right)^2 + 2 \left(\sum_{i=1}^{4} \frac{C_i}{C_3} \right) - 3 \right\}^{1/2}$$

$E_{G,Qm}(Q_4)$: like $E_{G,Qm}(Q_2)$ but permuting C_2 and C_4

Table A 4.4: Relative errors s_Q/Q_i occurring in the guard zone method for flow Q_i and caused by errors in the flow measurements. A constant exponent n is assumed.

Reference

Fürbringer, J.-M., Roulet, C.-A. [1991]: Study of the Errors Occurring in Measurement of Leakage Distribution in Buildings by Multifan Pressurization. *Building and Environment, 1991*

Appendix 5. Strength of the Passive PFT Sources

The passive tracer sources are made of a capsule partly filled with the liquid tracer and closed with a device allowing a small effusion flow rate of the tracer (see Section 5.2.2 of Part III). This Appendix presents the fundamental processes which occur in these sources and explains why the strength of these sources depends on the temperature.

A 5.1. Tracer Vapor Pressure

The saturation vapor pressure of the tracer gas enclosed in the capsule over the liquid surface depends on the temperature, following approximately an Arrhenius law:

$$p_s = p_{so} \exp(-E_p/RT) \qquad \text{(A 5.1)}$$

where:

- E_p is the activation energy for the vapor pressure [J/mole]
- R the molar gas constant ($R \approx 8.31396$ J/K)
- T the absolute temperature [K]
- p_{so} is the vapor pressure at infinite temperature.

A 5.2. Permeation Tracer Sources

In these sources, the tracer diffuses through a silicone rubber plug used to seal the source. The flow density [kg/(m^2.s)] of tracer through that plug follows the Fick's law:

$$\vec{\Phi} = - D \vec{\text{grad}}\, c \qquad \text{(A 5.2)}$$

where c is the concentration [kg/m^3] and D the diffusion coefficient [m^2/s]. This coefficient itself generally depends on the temperature, following also an Arrhenius law:

$$D = D_0 \exp(-E_D/RT) \qquad \text{(A 5.3)}$$

where:

- E_D is the activation energy for the diffusion [J/mole]
- D_o is the diffusion coefficient at infinite temperature [m^2/s].

If the Fick's equation is integrated, assuming a steady state and a zero concentration outside the cell, the mass flow S going out of that cell is:

$$S = A D c_s/L \qquad \text{(A 5.4)}$$

where:

- A is the area of the diffusion plug
- L is its length
- c_s is the concentration in the inside part of the plug.

There is a relation between the concentration and the saturation pressure p_s at a given, absolute temperature T:

$$c_s = K p_s \qquad \text{(A 5.5)}$$

where the solubility coefficient depends on the temperature, following another Arrhenius law with an activation enthalpy ΔH:

$$K = K_o \exp(-\Delta H/RT) \qquad \text{(A 5.6)}$$

Using equations A5.1, A5.3, and A5.6 in the equation A5.4, we get the temperature dependance of the flow:

$$S = \frac{A}{L} p_{so} D_o K_o \exp\left(-\frac{E_D+\Delta H+E_p}{RT}\right) \qquad \text{(A 5.7)}$$

It follows from these relations that the equilibrium mass flow through the plug depends on the

temperature.

Besides these effects, there are dynamic effects in the diffusion plug when the temperature changes: the concentration profile is no more linear and some time is required to adjust to a new concentration profile. These effects have a long time constant, and several days may be necessary after a temperature change to reach a constant flow rate.

A 5.3. Capillary Sources

These sources are closed by a capillary tube, and the tracer flow rate is determined by the diameter and length of that tube and by the tracer saturation pressure.

At atmospheric pressure, in the capillary tubes commonly used (about 0.2 mm diameter), the flow is dominated by the molecular diffusion process, as far as the atmospheric pressure does not vary too much and too often (no pumping effect). In this case, the above equations are still valid, but with another diffusion coefficient, D', since the tracer diffuses in air instead of silicon rubber. Moreover, the concentration gradient is directly proportional to the vapor pressure, and the delay to obtain a constant flow rate after a temperature change is much smaller (a few minutes). The temperature dependance of the flow rate is then:

$$S = \frac{A}{L} p_{so} D'_o \exp\left(-\frac{E_{'D}+E_p}{RT} \right) \qquad \text{(A 5.8)}$$

Appendix 6. Algorithm to Control a Constant Concentration System

A constant concentration tracer gas (CCTG) measuring system needs a control algorithm to calculate, at each sampling time, the required tracer gas injection rate to maintain the gas concentration at the target level.

This Appendix proposes an efficient control algorithm *[Compagnon, Kohler, Roecker, Roulet, 1988]*. Practical considerations concerning modifications to take into account the physical limitations of the CCTG system and the computing of the optimal control parameters are also presented. Note that another algorithm, used with mass flow controllers for the injection, is presented in part III, Section 6.3.2.

A 6.1. Single Zone Model

In a first step, let us consider a single zone. The equation governing the tracer gas concentration into the zone can be written, in a first approximation, as:

$$V \frac{dC}{dt} = q - QC \qquad \text{(A 6.1)}$$

where:

V: effective volume of the zone [m^3]
C: tracer gas concentration [-]
Q: air flow leaving the zone [m^3/s]
q: tracer gas injection into the room [m^3/s]

This equation assumes that the outside tracer gas concentration is negligible and that the air has a constant density. A perfect mixing of the tracer gas within the zone is also assumed. Even if these assumptions are not always true in real conditions, this model is sufficiently good for control purposes.

Since the CCTG system analyzes the concentrations in a zone by sampling at discrete times, the differential equation (1) should be integrated over one sampling time τ_s to give a difference equation:

$$C_{k+1} = a_k C_k + b_k U_k \qquad \text{(A 6.2)}$$

where: C_{k+1}, C_k: tracer gas concentration at time $(k+1)\,t_s$ and $k\,\tau_s$ respectively [-]

$U_k = q_k/V$: injection rate [s^{-1}]

$$a_k = \exp(-Q_k\tau_s/V) \quad [-] \qquad \text{(A 6.3)}$$

$$b_k = V(1 - a_k)/Q_k) \text{ if } Q_k > 0, \quad b_k = \tau_s \text{ if } Q_k = 0 \quad [s] \qquad \text{(A 6.4)}$$

τ_s: sampling time [s]
k: sample number [-]

The air flow Q_k and the injection rate q_k are assumed to be constant over the integrating time interval $[k\,\tau_s; (k+1)\,\tau_s]$.

A 6.2. Control Algorithm

The function of the control algorithm is to compute the necessary injection rate U_k to maintain the concentration at a target level denoted W_k (for complete generality the target level may also change during time : therefore it is also denoted by the sample number k). The injection rate is computed using the expression :

$$U_k = -K_s C_k + K_R X_{Rk} + K_w W_k \quad [s^{-1}] \qquad \text{(A 6.5)}$$

with:

K_s, K_R, K_w: parameters of the control algorithm [s-1]
X_{Rk}: an integrating term defined by the difference equation :

$$X_{Rk+1} = X_{Rk} + W_k - C_k \quad [-] \qquad \text{(A 6.6)}$$

This expression is derived by minimizing the quadratic form :

$$J = \sum_{k=0}^{\infty} [(W_k - C_k)\, Q_e\, (W_k - C_k) + X_{Rk}\, Q_R\, X_{Rk} + U_k\, R\, U_k] \qquad \text{(A 6.7)}$$

where Q_e, Q_R and R are weighting factors (see *[Bühler, 1983]* for full details).

Different methods are available for the determination of the parameters K_s K_R and K_w. We choose a method which consists of imposing the poles of the system. This method is far more practical to use for two reasons:

- It is not necessary to make an arbitrary choice of the weighting factors for the quadratic form
- The computing of K_s, K_R and K_w is easier and doesn't require complex computer code as the other methods.

In fact the two poles of the system depend only on the parameters K_s and K_R. The value of the third parameter K_w does not have any influence on the pole location but may be used to compensate the effect of one pole.

The relations between the poles and the parameters are :

First case : Real poles Z_1 and Z_2 (Z_1 is the compensated pole):

$$K_s = (-Z_1 - Z_2 + a_k + 1)/b_k$$

$$K_R = (1 - Z_1)(1 - Z_2)/b_k \qquad \text{(A 6.8)}$$

$$K_w = K_R/(1-Z_1)$$

Second case : Two complex conjugate poles $Z_{1,2} = \mathrm{Re}(Z) \pm i\ \mathrm{Im}(Z)$. The real part of the pole is compensated:

$$K_s = (-2\,\mathrm{Re}(Z) + a_k + 1)/b_k$$

$$K_R = [(\mathrm{Re}(Z) - 1)^2 + \mathrm{Im}^2(Z)]/b_k \qquad \text{(A 6.9)}$$

$$K_w = K_R/(1-\mathrm{Re}(Z))$$

where a_k and b_k are defined by (3) and (4).

Through a_k and b_k, the parameters K_s, K_R and K_w are functions of the sampling time τ_s and of the air change rate. There is apparently a problem here as the control algorithm requires parameters which depend on the varying air change rates not known before measurement! In fact, the control algorithm needs only an estimation of the air change rate and the parameters are calculated once for the entire measurement procedure. Moreover, if the poles are properly located, these parameters no longer depend on the air flow rate *[Compagnon, Kohler, Roecker, Roulet, 1988]*.

At the beginning of the measurement procedure, the integrating term X_{Rk} has to be initialized to a certain value. Under the assumption that the initial concentration C_o was kept constant in the past, the initial value X_{Ro} is defined by :

First case : Real poles Z_1 and Z_2 (Z_1 is the compensated pole):

$$X_{Ro} = C_o/(1-Z_2) \qquad \text{(A 6.10)}$$

Second case : Two complex conjugate poles (the real part of the poles is compensated):

$$X_{Ro} = C_o/(1 - \mathrm{Re}(Z)) \qquad \text{(A 6.11)}$$

A 6.3. Advantages of the Algorithm

The proposed control algorithm defined by equation (A 6.5) looks like a special case of a traditional PI control algorithm. In fact this algorithm presents some advantages over the usual PI control method.

First, a faster response to a step change in the target concentration W_k is obtained by the pole compensation (fig. A 6.1). This property is very useful for measurement procedures using variable target concentrations in multizone buildings.

Secondly, the minimization of a quadratic form is well suited to generalize into a multivariable control algorithm. Thus an extension of this algorithm to the case of a multizone measurement system is not

difficult. This extension is summarized as follows : equation (1) is rewritten using matrix notation:

$$V \frac{d}{dt} C = q - Q C \qquad \text{(A 6.12)}$$

where:

V : volumes diagonal matrix [m^3]
C : concentrations vector [-]
Q : air flows matrix [m^3/s]
q : tracer gas injections vector [m^3/s]

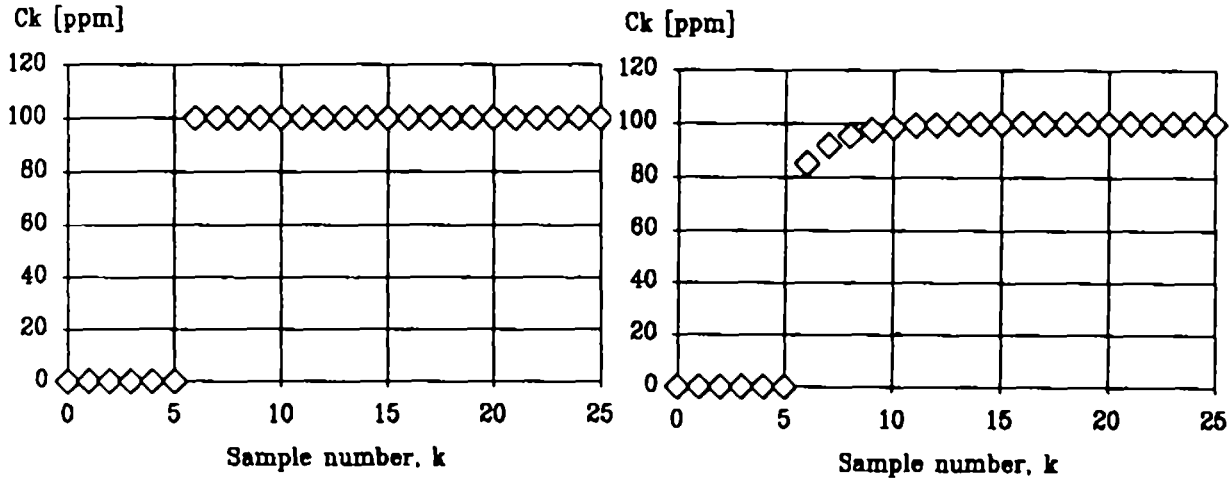


Figure A 6.1: Response of the control algorithm for a target level step from 0 to 100 ppm change just after sample 5: the new control algorithm (left) has a faster response than the PI control method (right). Values computed with 1 air change/hour and τ_s = 540 [s].

The difference equation (A 6.2) becomes :

$$C_{k+1} = A C_k + B U_k \qquad \text{(A 6.13)}$$

where A and B are matrixes derived from the air flows matrix Q and the volumes matrix V and

$$U_k = V^{-1} Q_k \qquad \text{(A 6.14)}$$

From equation (A 6.13), various methods are available *[Bühler, 1983]* to compute the parameters matrixes K_s, K_R and K_w necessary for the control algorithm defined (similar to equation (A 6.5) by :

$$U_k = - K_s C_k + K_R X_{Rk} + K_w W_k \qquad \text{(A 6.15)}$$

where W_k is the target concentrations vector and X_{Rk} the integrating vector defined by the difference equation :

$$X_{Rk+1} = X_{Rk} + W_k - C_k \qquad \text{(A 6.16)}$$

A 6.4. Modifications of the Algorithm

The tracer gas injection rate that the apparatus can supply is limited to a certain range: no tracer gas can be removed from the zone and a maximum injection rate can not be exceeded. Figures A 6.2 and A 6.3 show two cases where these limitations lead to large over- or under-shoots of concentration.

These problems are caused by inappropriate values of the integrating term X_{Rk}. Although the CCTG system cannot supply the necessary injection rate or remove gas to readjust the concentration to target level, the value of X_{Rk} is still increased or decreased as if the system had no limitations. This results in too high or too low values of X_{Rk}, and it takes several steps with over or under concentration to correct the value of this term.

To avoid these problems, it is necessary to correct the value of X_{Rk} when the system is unable to supply the injection rate the control algorithm has asked for. Among the many possibilities to adjust these values, two procedures are presented here:

First case : negative calculated injection rate $U_k < 0$

Negative values typically occur after a concentration overshoot due to an abrupt decrease of the air infiltration rate into the zone (fig. A6.2). The control algorithm wants to remove tracer from the zone. As seen above (equation A6.5), the injection rate is proportional to W_k, - C_k and X_{Rk}. During the whole overshoot while $C_k > W_k$, the integrating term decreases. Then, when the concentration goes below the target level, because of the low value of X_{Rk}, the injection rate remains negative and it takes several steps with $C_k < W_k$ to raise the value of X_{Rk} to its new stationary value allowing positive injection rate to be computed.

To avoid this undershooting, the integrating term could be adjusted just before the decreasing concentration crosses the target level. Thus, this procedure works as follows :

Whenever the control algorithm computes a negative injection rate, the actual infiltration rate is estimated and the concentration for the next step can be extrapolated. If, without any gas injection, the extrapolated concentration is still above target level, nothing is done. But in the other cases, the integrating term is forced to a value leading, through the use of control equation (A6.5), to the necessary injection rate to reach the target level. The following relations are used for this procedure, assuming $U_k < 0$):

estimated actual air change rate :

$$n_{est} = \text{Ln}\,([C_{k-1} + \tau_s \max(0; U_{k-1})]/C_k)/\tau_s \qquad 17)$$

(if $U_{k-1} > 0$ n_{est} underestimates the true air change rate)

predicted concentration :

$$C_{p\,k+1} = C_k \exp(-n_{est} \cdot \tau_s) \qquad \text{(A 6.18)}$$

necessary injection rate (if $C_{p\,k+1} < W_{k+1}$) :

$$U_k^* = \frac{C_k}{t_s}\left(\frac{W_{k+1}}{C_{p\,k+1}} - 1\right) \qquad \text{(A 6.19)}$$

new value for the integrating term :

$$X_{Rk}^* = (U_k^* + K_s C_k - K_w W_k)/K_R \qquad \text{(A 6.20)}$$

Since the actual air change rate is computed over one sampling time only, its value is sensitive to any measurement error. Therefore equation (A6.19) gives an underestimate of the necessary injection rate to avoid large effects from small measurement errors (it is always easier to add some gas at the next step than to remove some !).

A comparison between fig. A6.2 and fig. A6.3 shows the effect of this procedure.

Second case: $U_k > U_{max}$, calculated injection rate too high

This case may occur at the beginning of a measurement on a large zone or when the air infiltration rate is very high. For extreme cases, the target concentration will never be reached.

Figure A6.4 illustrates the problem: the increase of the concentration is limited by U_{max} while the integrating term increases. When the concentration reaches the target level, the high integrating term value forces the control algorithm to inject too much gas. This leads to a concentration overshoot until the integrating term finds its stationary value again.

To avoid this phenomenon, each time the control algorithm asks for an injection rate higher than U_{max}, the integrating term is forced to a proper value. This value is calculated so that, when used in the control equation (A6.5), the maximum possible injection rate U_{max} results.

The new value of the integrating term is then, assuming $U_k > U_{max}$:

$$X_{Rk}^* = (U_{max} + K_s C_k - K_w W_k)/K_R \qquad \text{(A 6.21)}$$

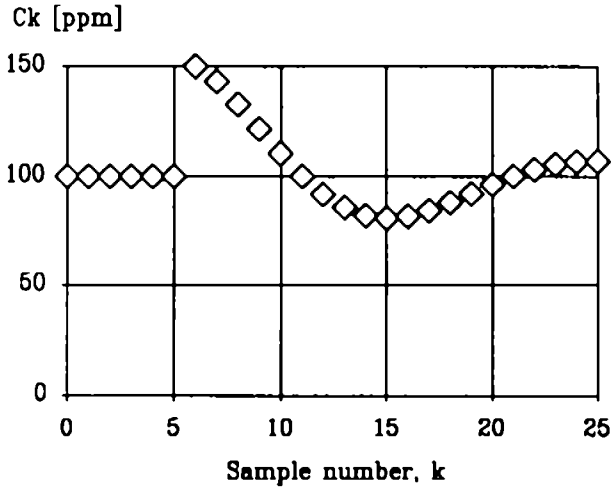


Figure A6.2: Concentration overshoot due to an abrupt decrease of the air change rate, with unmodified algorithm.

Values computed with V = 80 [m3] and t_s = 540 [s].

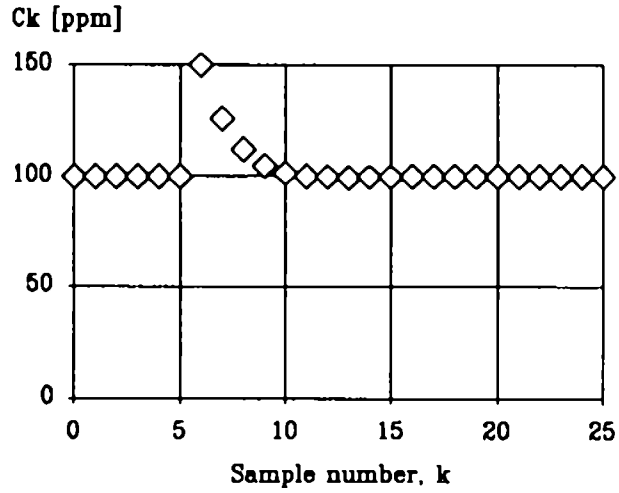


Figure A6.3: Effect of the first modification of the control algorithm (compare with fig. A6.2).

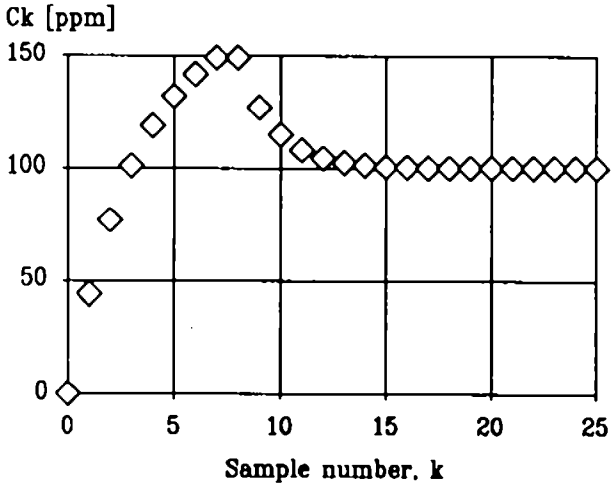


Figure A6.4: Concentration overshoot due to the limiting effect of the maximum injection rate, U_{max}, the CCTG system is able to supply. These values lead to the maximum concentration increase at the first step: $C_1 = b\ Umax = 28{,}4$ [ppm].

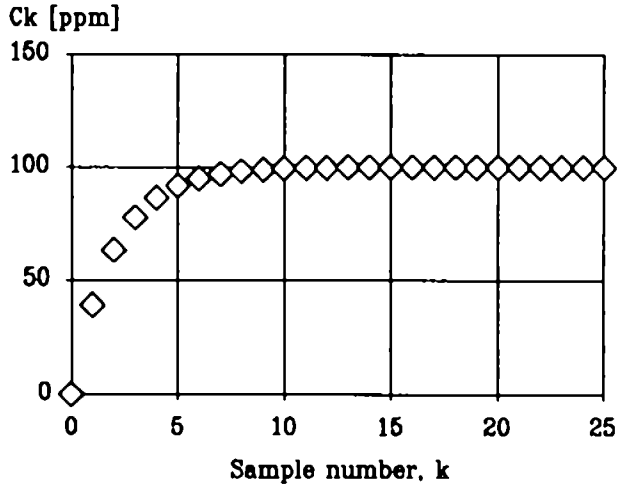


Figure A6.5: Effect of the second modification of the control algorithm (compare with fig. A6.4).

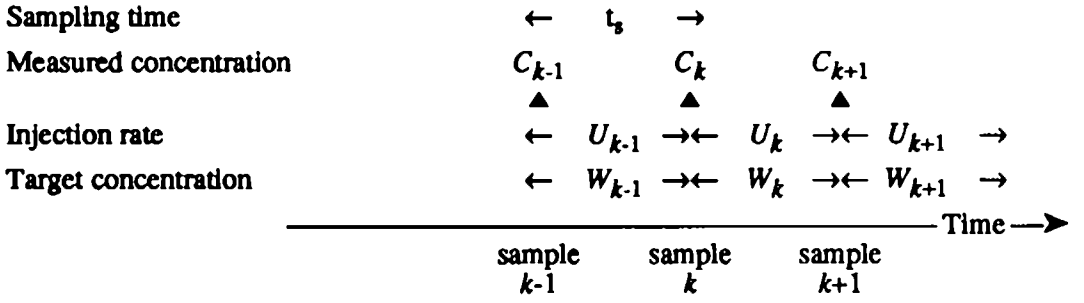
Values computed with V = 200 [m^3], t_s = 540 [s] and Umax = 5.67.10^{-8} [s^{-1}].

A 6.5. Implementing the Algorithm

This paragraphs provides the detailed information necessary to implement the control algorithm in a program calculating the injection rate.

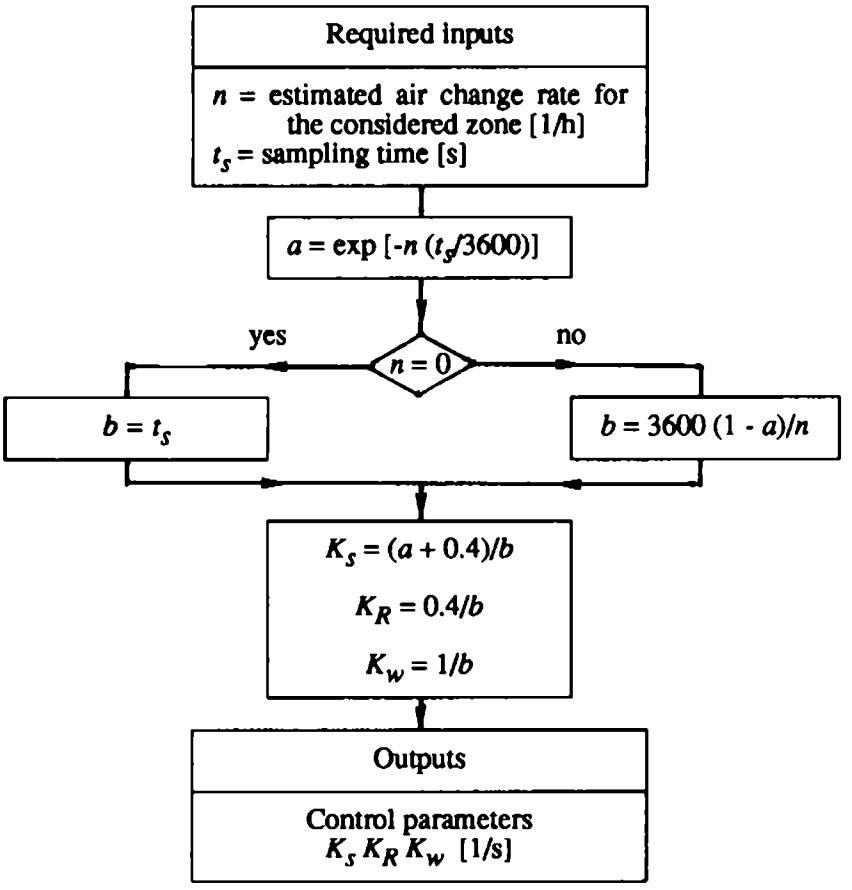
Each zone is individually controlled. The following algorithms are designed for a single zone. In case of a multizone application, simply use the same algorithm for each zone separately, as well as for each gas in multitracer system.

Time-dependent variables are referenced by their sample number k defined by :



Computing of the control parameters K_S, K_R and K_W

Equations (8) are used with poles located at $Z_1 = 0.6$ $Z_2 = 0$, which is one of the best possibilities.



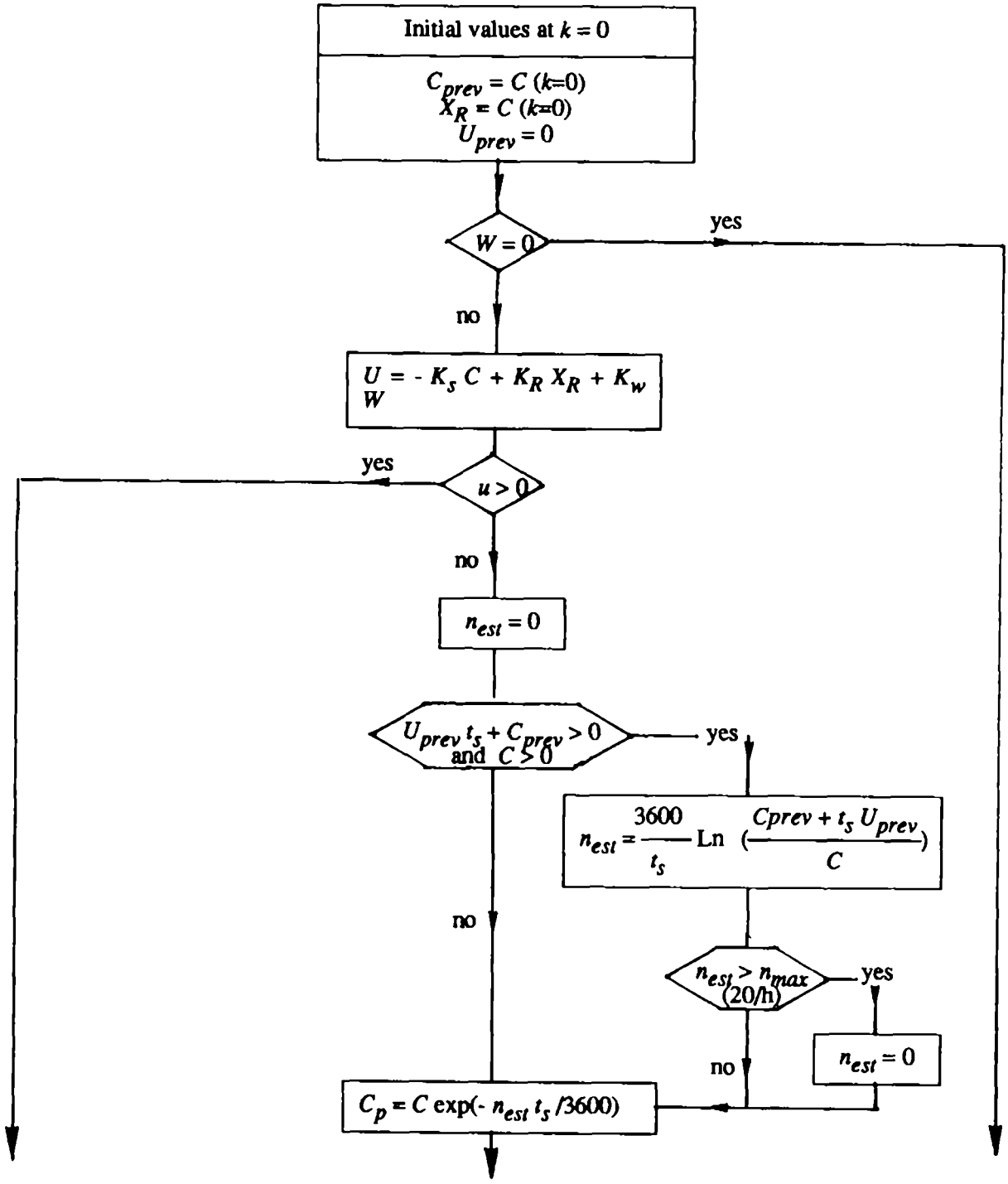
Control algorithm computing the necessary tracer injection rate at sample k.

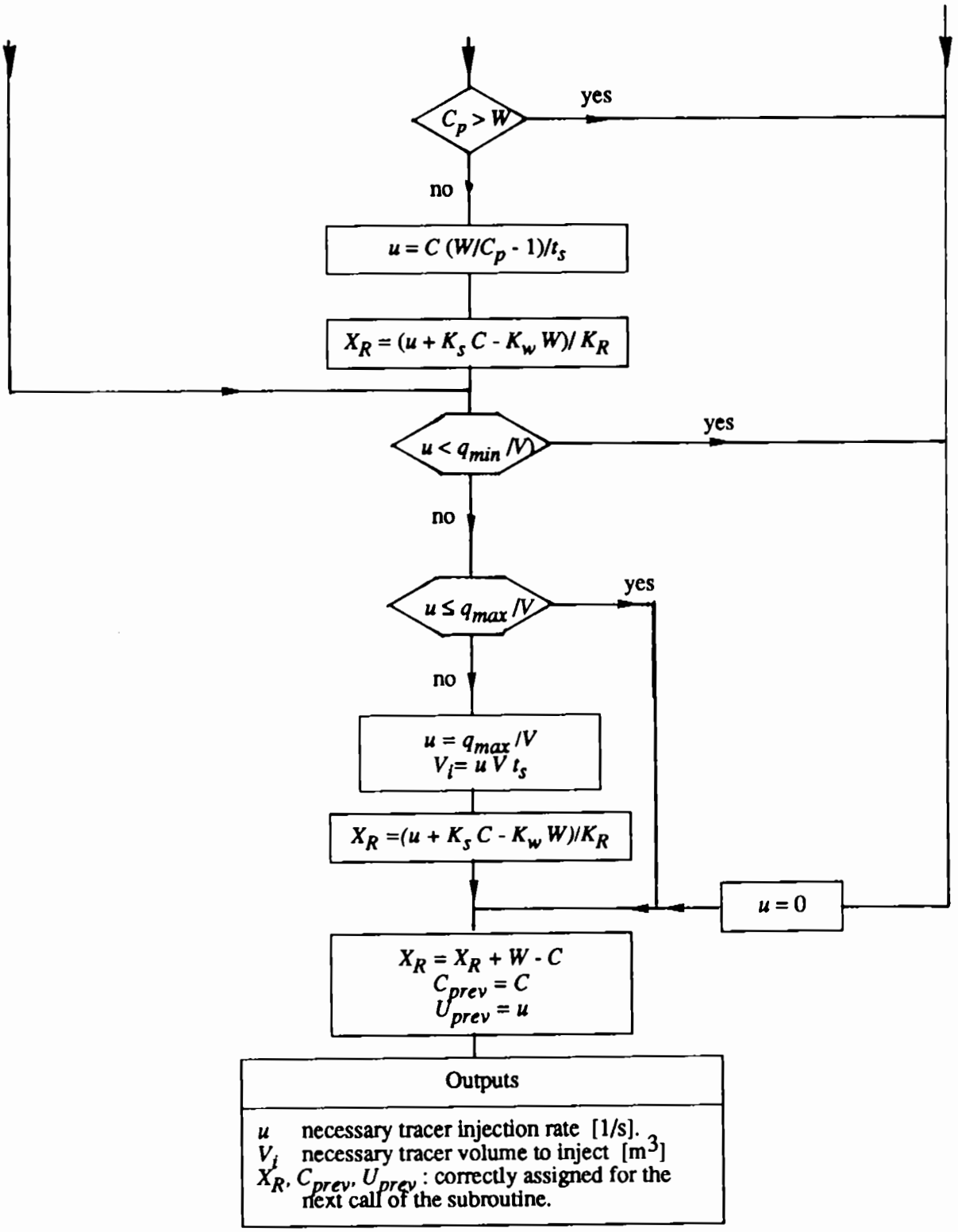
Constant required input:

V	volume of the zone [m3]
q_{max}	maximum tracer injection rate the system is able to provide [m^3/s]
q_{min}	minimum non-zero tracer injection rate the system is able to provide [m^3/s]
n_{max}	maximum expected air change rate [1/h]
K_s, K_R, K_w	control parameters [1/s]
t_s	sampling time [s]
C	measured concentration at sample k [-]

Time dependant inputs:

C_{prev}	previous measured concentration [-]
W	target concentration at sample k [-]
X_R	integrating term [-]
U_{prev}	previous tracer injection rate [1/s]




$C_p > W$
yes
no
$u = C\,(W/C_p - 1)/t_s$
$X_R = (u + K_s\,C - K_w\,W)/\,K_R$
$u < q_{min}\,/V$
yes
no
$u \leq q_{max}\,/V$
yes
no
$u = q_{max}\,/V$
$V_i = u\,V\,t_s$
$X_R = (u + K_s\,C - K_w\,W)/K_R$
$u = 0$
$X_R = X_R + W - C$
$C_{prev} = C$
$U_{prev} = u$
Outputs
u necessary tracer injection rate [1/s].
V_i necessary tracer volume to inject [m^3]
X_R, C_{prev}, U_{prev} : correctly assigned for the next call of the subroutine.

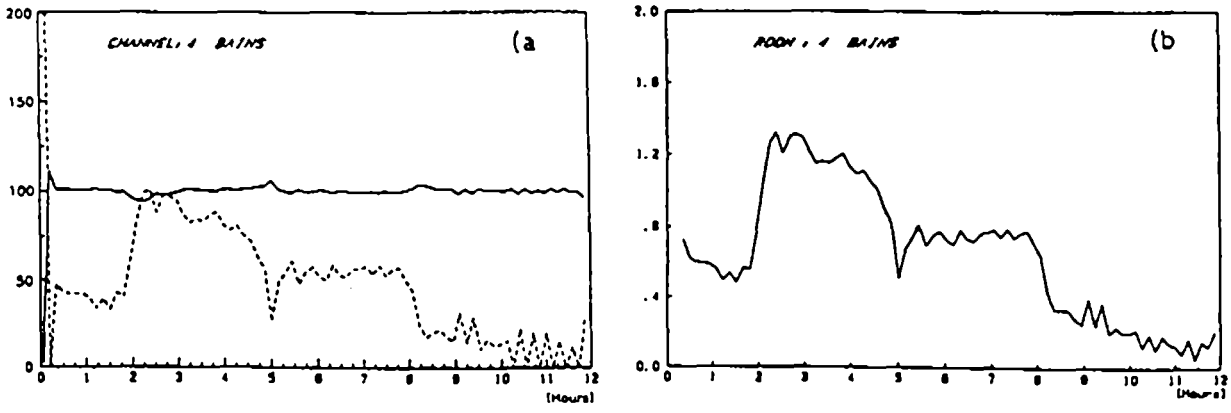


Figure A6.6: Measurements in a mechanically ventilated, inhabited bathroom [11].

a) Concentrations [ppm] *measured during 12 hours within a bathroom (V = 14.1 [m3], target level W = 100 ppm, τ_s = 525 [s]). Dotted line shows the tracer injection rate (arbitrary units).*

b) Air change rates [h^{-1}] *deduced from the CCTG measurement. Large air change rate variations due to the mechanical ventilation system can be observed.*

A 6.6. References

Compagnon R., Kohler A., Roecker C., Roulet C.-A. [1988] Development of an efficient control algorithm for a multizone constant concentration tracer gas infiltration measurement system. *9th AIVC conference, Gent,* 1988.

Bühler H. [1983]: Réglages échantillonnés (Volume 2 : traitement dans l'espace d'état) *Presses Polytechniques Romandes, Lausanne, 1983.*

Appendix 7. Glossary

Items in *italics* are other entries in the glossary.

AC pressurization technique

Evaluating the *air leakage* of a building using a piston assembly to vary the *effective volume* of the structure and measuring the pressure response due to this variation.

Acoustic leak detection technique

A method of detecting cracks in a building where leakage may occur by placing a steady source of high pitched sound within the building and using a microphone outside as a detector. Leaks correspond to an increase in volume of the sound transmitted. This technique provides qualitative information only.

Age of the air (or age of a contaminant)

Average time period since the fresh air (or a contaminant) entered the room or the building. This age depends on the location in the building. The *room mean age* is the average of the age over the whole room.

Air change performance

Coefficient defined by ASHRAE, which is the double of the *air exchange efficiency*.

Air change rate (also called *Specific flow rate*)

The ratio of the volumetric rate at which air enters (or leaves) an enclosed space divided by the volume of that space. Often this is expressed in air changes per hour. Its inverse is the *nominal time constant*.

Air exchange efficiency

Efficiency of the ventilation to change the air in a room. It is half the ratio of the *nominal time constant* and the *room mean age*.

Air exchange rate

General term relating to the rate of air flow between one space and another. This can be between various internal zones of a building or between the building and the atmosphere.

Air exfiltration

The uncontrolled leakage of air out of a building.

Air flow coefficient

Coefficient in the air *leakage characteristics* which has the dimension of an air flow. This coefficient multiplies the *pressure differential* at a power exponent.

Air flow rate

The mass or volume of air moved in unit of time. (The transport may be within an enclosure or through an enclosing envelope).

Air infiltration

The uncontrolled inward *air leakage* through cracks and interstices in any building element and around windows and doors of a building (i.e., adventitious openings), caused by pressure effects of the wind and/or the effect of differences in the indoor and outdoor air density.

Air infiltration characteristic

The relationship between the infiltration *air flow rate* into a building and the parameters which cause the movement.

Air leakage

The flow of air through a component of the building envelope, or the building envelope itself, when a pressure difference is applied across the component.

Air leakage characteristic

An expression which describes the *air leakage* rate of a building or component. This may be:

(a) the air leakage flow rate at a reference pressure difference across the component or building envelope.

(b) the relationship between flow rate and the pressure difference across the building envelope or component.

(c) the *equivalent leakage area* at a reference pressure difference across the component or building envelope.

Airtightness

A general descriptive term for the *leakage characteristics* of a building.

Analyzer

Instrument used to measure the *concentration* of a *tracer gas* or a *contaminant* in a sample of air.

Anemometer

Any instrument measuring the air speed or the air velocity

Background concentration

Concentration of a gas in outdoor air.

Background leakage

Leakage of air through a building envelope which is not accounted for by obvious measurable gaps.

Balanced fan pressurization

Technique utilizing two or more *blower doors* to evaluate the leakage of individual internal partitions and external walls of multizone buildings. Technique involves using the fans to induce a zero pressure difference across certain building components, thus eliminating their leakage from the measurement.

Balanced ventilation

A system in which fans both supply and extract air from the enclosed space, the supply and extract flow rates being equal.

Blower door (also called Fan Door)

A device that fits into a doorway for supplying or extracting a measured flow rate of air to or from a building. It is normally used for testing for air leakage by *pressurization* or depressurization.

Building component

General term for any individual part of the building envelope, usually applied to doors, windows and walls.

Building envelope

The total of the boundary surfaces of a building, through which heat (or air) is transferred between the internal spaces and the outside environment.

Calibration

Operation where the output of a measuring device is compared with reference standards in order to accurately quantify the results provided by the measuring device.

Capacitance pressure transducer

A device with a metal diaphragm sensing element acting as one plate of a capacitor. When pressure is applied it moves with respect to a fixed plate, changing the thickness of the dielectric between. The resulting signal is monitored using a bridge circuit.

Cell

Volume in a *room* limited by a theoretical or physical surface, in which the physical quantities of interest can be considered as homogeneous. A room can be divided in several cells.

Chemical indicator tubes (also called Dräger tubes)

Glass tubes containing an adsorbing material which color changes in the presence of a specific gas.

Collector chamber

Sealed box or other enclosure used to isolate a building component when conducting *Pressurization tests*.

Compensated flow meter

Air flow rate measuring instrument in which a fan compensates the pressure drop required by

the measuring device.

Component leakage

The leakage of air through the building envelope or internal partitions, which is directly attributable to flow through cracks around doors, windows and other components.

Concentration

Ratio expressing the amount of a chemical component in a mixture. This ratio may be expressed in terms of mass, of volume, or of number of molecules. In air, it can also be the ratio of the mass of component divided by the volume of air.

Condition number

Number expressing how much the errors in measured data are enlarged when transmitted, through the interpreting equations, to the final results.

Conductance

Generally, any path allowed for air between two *zones*. Also the ratio of the flow rate through a path to the *pressure differential* across that path..

Connected space

A space in a building adjacent to the measurement space with which significant exchange of air may take place, thus increasing the *effective volume* of the space.

Constant concentration technique

A method of measuring ventilation rate whereby an automated system injects *tracer gas* at the rate required to maintain the concentration of tracer gas at a fixed, predetermined level. The ventilation rate is proportional to the rate at which the tracer gas must be injected.

Constant injection rate technique

A method of measuring ventilation rate whereby tracer is emitted continuously at a uniform rate. The equilibrium concentration of *tracer gas* in air is measured.

Contaminant

An unwanted airborne constituent that may reduce the acceptability of the air.

Contaminant removal effectiveness

see *Ventilation effectiveness*

Continuity equation (also called *Mass balance*)

Mathematical expression relating to the conservation of matter, an example of which is the equation equating the flow of *tracer gas* into a space with the flow of tracer gas out of a space. This particular equation is the basis for evaluating air exchange rates from tracer gas measurement.

Cup anemometer

A device for measuring wind speed comprising a number of cups attached around a spindle to which an indicator is fitted. Widely used in meteorological studies.

Damper

Adjustable plate in a duct for controlling the flow rate.

DC pressurization

Airtightness measuring technique using a fan to pressurize the measured volume at a constant pressure. See also *Fan pressurization.*

Decay rate technique

A method of measuring ventilation rate whereby a quantity of *tracer gas* is released and the decrease in concentration measured as a function of time.

Deduction method

Multifan testing method in which the *pressure differential* between two *zones* of a building is changed step by step in order to obtain the *leakage characteristics* of building elements in these zones.

Density

Ratio of the mass of a quantity of matter to its volume.

Depressurization

Term used to describe fan pressurization when a static under pressure is created within the building.

Differential pressure

See *Pressure differential*

Discharge coefficient

A dimensionless coefficient relating the mean flow rate through an opening to an area and the corresponding pressure difference across the opening.

Displacement flow (also called Piston flow)

With this type of flow incoming outdoor air displaces internal air without mixing.

Distribution effectiveness

Ratio of the average *tracer gas* or *contaminant concentration* to the concentration which could be reached, at equilibrium, in the same *zone* or building with the same tracer or contaminant sources. Also the ratio of the contaminant or tracer *turn-over time* to the *room mean age* of air. It is the inverse of the relative *contaminant removal effectiveness*.

Door panel

Panel adapted to a door or a window, on which the *pressurization* fan is adapted.

Draft gauge

Inclined U-tube *manometer*.

Dräger tubes

See *chemical indicator tubes*

Effective volume

The volume of the interior building (or *room*) in which mixing occurs.

Efficiency of the ventilation system

Ratio of the fresh air provided by the ventilation system to an enclosure to the total amount of air entering the room, including *infiltration*.

Electron capture detector

An instrument which uses a weak beta source to generate electrons in an ionization chamber, which is subjected to a pulsed voltage, thus generating a current. Electron capturing material in the sample reduces the number of electrons in the chamber and thus the current. This reduction can be calibrated in terms of *tracer gas concentration*, hence the concentration of tracer gas in an air sample can be evaluated.

Envelope (of a building)

See *Building envelope*

Equivalent leakage area (ELA)

The equivalent amount of orifice area that would pass the same quantity of air as would pass collectively through the building envelope at a specified reference pressure difference.

Experimental design

The way an experiment is planned, or, more precisely, a list of values of controlled parameters at which measurements should be performed to obtain the required results.

Extract ventilation

A *mechanical ventilation* system in which air is extracted from a space or spaces, so creating an internal negative pressure. Supply air is drawn through adventitious or intentional openings.

Fan pressurization

General term applied to any technique involving the production of a steady static *pressure differential* across a building envelope or component. Often referred to as *DC Pressurization*.

Flame ionization detector

Detector used in conjunction with a *gas chromatographer*, in which the change in ionic current caused in a hydrogen-air flame by a tracer or contaminant is detected. This detector is

sensitive to organic compounds.

Flow coefficient

In the power function approach this parameter is used in conjunction with the "*flow exponent*" to quantify flow through an opening.

Flow equation

Equation describing the *air flow rate* through a building (or component) in response to the pressure difference across the building (or component). These equations are usually *power law* or in form.

Flow exponent

In the power function approach this parameter characterize the type of flow through a component. ($n = 1$ represents laminar flow, $n = 0.5$ represents turbulent flow). For most flow paths, n takes a value between these extremes.

Fortuitous leakage

Uncontrolled air leakage through building envelope due to the natural action of wind and temperature, i.e., *air infiltration*.

Gas chromatography

A process by which gases can be separated from one another. Used in this application to separate *tracer gases* from each other and from the constituents of air, thus allowing individual analyses to be performed.

Gasometer

Instruments to measure volumes of any gas.

Grab sampling method

Any *tracer gas* method where air/tracer samples are obtained from a building and analyzed afterwards in a laboratory.

Guard zone technique

Dual-fan *pressurization* technique used to measure the *leakage characteristics* of a building part. One fan is used to pressurize a guarding *zone*, surrounding the guarded zone in which the other fan just maintains a zero *pressure differential* between these zones. The measured building part is the only unguarded part.

Hot wire anemometer

Anemometer in which the air velocity is determined by the temperature of a heated wire exposed to the wind.

Indoor air pollution

Pollution occurring indoors from any source i.e., from outside as well as inside the building.

Infra-red gas analyzer

Instrument used to determine *tracer gas concentrations* by determining the transmission of infra-red radiation at an absorption frequency through a fixed path length.

Interzonal air flow

General term applied to the process of air exchange between internal *zones* of a building.

Leakage characteristics

Equation relating the *air flow rate* through a leak and the *pressure differential* across this leak. This relation involves the *flow coefficient* and the *flow exponent*.

Leakage path

A route by which air enters or leaves the building or flows through a component.

Leakage site

A point on the outer or inner surfaces of a *building envelope* or an internal wall where a *leakage path* emerges.

Leakage area

See *Equivalent leakage area*

Leeward
: Downwind side of any object.

Local mean age
: Average time period spent by air particles to reach a location in an enclosure since they enter that space.

Manometer
: A device for measuring pressure employing the principle of displacement of liquid levels in a liquid filled "U" tube. The limbs of the "U" may be vertical, inclined (*draft gauge*) or curved.

Mass balance
: see *Continuity equation.*

Mass flow controller
: Device controlling the flow rate of a gas by means of a valve controlled according the measurement of the mass flow rate.

Mass spectrometry
: Technique allowing the quantitative measurement of amounts of different gases, based on the separation of the ionized gas molecules according their mass to charge ratio.

Mean age of air
: See *Local mean age.*

Mechanical ventilation
: Ventilation by means of one or more fans.

Mixing
: The degree of uniformity of distribution of outdoor air or foreign material in a building.

Mixing fan
: Small electric fan used to aid the mixing of room air and *tracer gas* before and/or during a measurement.

Multiple tracer gas technique
: General term applied to measurement methods using two or more *tracer gases*. These methods are often used to evaluate interzonal air flows.

Multizone
: A building or part of a building comprising a number of *zones* or *cells*.

Natural ventilation
: Ventilation using only purpose provided openings and the natural motive forces of wind and temperature difference.

Nominal time constant
: The ratio of the volume of an enclosed space divided by the volumetric rate at which air enters (or leaves) that space. Its inverse is the *air change rate*.

Normalized leakage area
: *Equivalent leakage area* expressed per unit *building envelope* area.

Orifice plate
: A device for measuring gas flow by measuring the pressure drop across an orifice in the flow line.

Outdoor air
: Air from free atmosphere that is generally assumed to be sufficiently uncontaminated to be used for ventilation.

Passive sampling
: Method of sampling *tracer gas* in a building by the process of passive diffusion.

Passive tracer source

Small container injecting continuously a small flow of tracer (mostly *PFT tracers*) by passive diffusion through its cover cap.

Perfluorocarbon tracers or PFT

Tracer gases composed by a family of perfluoroalkylcycloalkanes, i.e.. cyclic organic compounds in which the hydrogen atoms are all replaced by fluorine atoms. These tracers can be analyzed in trace amount because the background concentration is low and the *electron capture detector* is very sensitive to them.

Photoacoustic detector

Tracer gas analyzer in which the alternative expansion of the gas sample irradiated with a chopped beam of convenient wavelength is detected with a microphone.

Piston-type ventilation

See *Displacement flow*

Pitot tube

Anemometer measuring the difference between the pressure in a tube facing the flow, in which the flow is stopped and the pressure along a side of the tube.

Pollutant removal effectiveness

see *Ventilation effectiveness*

Pollution migration

Descriptive term for the movement of indoor air pollutants throughout a building.

Pollution source

Any object, usually within a building, which produces a substance which will contaminate the internal environment.

Power law

Flow equation in which the *air flow rate* through the *building envelope* is proportional to a power of the *pressure differential.*

Ppm

Unit for expressing concentration, which is a part per million (10^{-6}).

Pressurization

Term used to describe *fan pressurization* when an excess static pressure (over-pressure) is created within the building.

Pressure differential

Usual term for the difference in pressure across *building envelope* or component whether caused by natural or artificial means.

Pressure tap

Point at which pressure is measured.

Pulse injection technique

Tracer gas measuring technique in which the tracer is injected in a short pulse.

Purging flow rate

Part of the *air flow rate* which effectively removes the *contaminants* out of the location of interest. It is the product of the air flow rate by the *ventilation effectiveness.*

Purpose provided openings

Openings in the *building envelope* for the specific purpose of supplying or extracting ventilation air.

Quadratic law

Flow equation in which the *pressure differential* is related to the *air flow rate* by a quadratic polynomial.

Reductive sealing method

A method of determining the leakage of specific building components by pressurizing the building and recording the leakage changes as components are sealed successively. When all the major outlets and component cracks are sealed, the remainder is the *background leakage.*

Relative contaminant removal effectiveness

Ratio of the concentration which could be reached, at equilibrium, in the same zone or building with the same tracer or contaminant sources, to the average tracer or *contaminant concentration.* Also the ratio of the *room mean age of air* to the contaminant or tracer *turnover time.* It is the inverse of the *distribution effectiveness.*

Residence time

See *Age of air*

Residual gas analyzer

See *Mass spectrometry.*

Retrofit

The process of reducing energy loss in a building by physical means, e.g. reducing excess air infiltration by obstructing flow through cracks and openings.

Reynolds number

Ratio of the inertial force to the friction force. It is also the ratio of the velocity of a fluid to its dynamic viscosity, multiplied by a typical dimension, e.g. the duct diameter.

Room

Volume of a building limited by building elements. In ventilation technique, this concept keeps its usual meaning. A room may be divided in several *cells* and several rooms may be combined in a *zone.*

Room mean age of air

Average of the *mean age of air* over the whole *room.*

Sample container

Container used to obtain a sample of air/tracer mixture from a measured building. The sample is usually returned to laboratory for analysis.

Short circuiting

A direct flow path between an air supply point and an air extract point, i.e., air flows along the shortest path, without mixing.

Single tracer gas technique

General term applied to any method using only one *tracer gas.* These methods are usually used to evaluate *air change rate.*

Single-zone

Any case where a building or part of a building is considered to be a single well mixed space.

Site analysis

Applied to any *tracer gas* measurement technique where traces of *air exchange rates are* determined directly at the measurement building.

Smoke leak visualization

A method of detecting leaks in the building fabric by pressurizing the building and using smoke to trace the paths followed by the leaking air.

Specific air flow rate (also called *Air change rate*)

The ratio of the volumetric rate at which air enters (or leaves) an enclosed space divided by the volume of that space. Its inverse is the *nominal time constant.*

Specific leakage area

Equivalent leakage area expressed per unit floor area.

Stack effect

Pressure differential across a *building envelope* caused by differences in the density of the air due to an indoor-outdoor temperature difference.

Step injection technique

Tracer gas measurement technique in which the tracer is injected at constant rate, starting from a given time.

Supply ventilation

A system in which air is supplied to a space(s) so creating an internal positive pressure. Air leaves the building through adventitious or purpose provided openings.

Tachometer

Instrument for measuring velocity or speed of rotation. Used to evaluate the speed of fans, this in turn is used to calibrate the fan in terms of air flow. Often used in *blower doors*.

Thermography

The process of converting the heat emitted from an object into visible pictures. Used to indicate and represent the temperature distribution over part of a building envelope.

Thermometer

An instrument that measures temperature.

Tracer gas

A gas used at low concentration, together with an analyzer, to determine *air flow rates* or other related quantities.

Tracer gas analyzer

Any instrument used to evaluate the concentration of *tracer gas* in a sample of air.

Tracer gas injection

Any process by which *tracer gas* is released into a space.

Tracer gas sampling

Any process by which *tracer gas* or air containing tracer gas is obtained for analysis.

Turn-over time of a contaminant

Ratio of the mass of *contaminant* contained in an enclosure to the mass flow rate of the contaminant source in this enclosure.

Ventilation

The process of supplying and removing air by natural or mechanical means to and from any space.

Ventilation effectiveness

An expression describing the ability of a mechanical (or natural) ventilation system to remove pollution originating in a space, either of a steady state or transient nature.

Ventilation energy

Energy loss from a building due to ventilation.

Venturi tube

Duct with a restricted section, which allows the measurement of the flow rate trough the pressure differential between the restricted and the normal section.

Wind vane

Device used to evaluate and/or record the direction of the prevailing wind.

Windward

Upwind side of any object.

Zone

Part of a building which is considered as a single volume for the experiment performed or the physical quantity of interest. A zone may contain several *rooms*.

Index

The roman numbers (I, II, to V) refer to the Parts and A to the Appendices. The Arab numbers refer to the page number in the corresponding Part.

THE AIR INFILTRATION AND VENTILATION CENTRE was inaugurated through the International Energy Agency and is funded by the following thirteen countries:

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