

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 industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation 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 (CRD), 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 behaviour 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 standardisation 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, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States of America.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 1

MEASUREMENT TECHNIQUES FOR VENTILATION
AND AIR LEAKAGE

PETER S. CHARLESWORTH

Air Infiltration and Ventilation Centre
Old Bracknell Lane West
Bracknell
Berkshire
RG12 4AH
Great Britain

SYNOPSIS

Ventilation has a considerable influence on both the indoor air quality and energy consumption of buildings. Three parameters can be identified which are of key importance in the assessment of ventilation behaviour:

- air change rate
- interzonal air flows
- air leakage characteristics

This paper describes measurement techniques which enable these parameters to be evaluated. The list of techniques presented is not exhaustive and the descriptions given are not particularly detailed. The main aim of this report is to illustrate the spectrum of techniques which are currently available for the quantification of ventilation and air leakage.

1. INTRODUCTION

It is necessary to understand the process of ventilation since it affects both the energy consumption and internal environment of a building. While recognising the need to supply a certain amount of fresh air to enclosed spaces, it must be realised that excessive ventilation may place an undue burden on a building's heating system. Insufficient ventilation will have an adverse effect on internal environments, making them uncomfortable or, in extreme cases, harmful to building occupants. Therefore the principle task, with regard to ventilation, is to minimise energy consumption while still maintaining indoor air quality. In order to assist the assessment of the ventilation characteristics of buildings, three key parameters may be identified.

1.1 Air Change Rate

This is a measure of the bulk movement of air into and out of a building and is defined as the volumetric rate at which air enters or leaves an enclosed space divided by the volume of the space. The air change rate, N , is a variable parameter which is dependent upon climatic forces, building construction, mechanical ventilation systems and occupant effects. Its main importance lies in heat load calculations and the stipulation of ventilation requirements. For example, an approximate expression for the heat loss in a building due to the ingress of cold air can be given by

$$H_V = 0.33 NV (T_i - T_e) \quad W \quad [1]$$

where H_V = heat loss due to ventilation, W
 N = air changes per hour, h^{-1}
 V = volume of the building, m^3
 T_i = internal temperature, K
 T_e = external temperature, K

1.2 Interzonal Air Flows

The bulk movement of air into and out of a building causes air to flow between the various internal spaces of the structure. Interzonal air flows are of particular importance in relation to the movement of airborne contaminants 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 structure. Thus these air flows cannot be ignored when considering the ventilation process.

1.3 Air Leakage Characteristics

Air enters and leaves a building through openings in the thermal envelope. These openings may be adventitious or purpose provided and the actual flow through them will be dependent on the air leakage characteristics of the openings and the prevailing climatic conditions. A knowledge of air leakage characteristics enables buildings to be evaluated and compared without interference from variable weather parameters. In addition, the evaluation of building leakage characteristics is the first step towards the mathematical modelling of the ventilation process.

Several measurement techniques have been developed which enable air change rate, interzonal air flows and air leakage characteristics to be evaluated. This paper identifies some of these techniques, examines their theoretical background and practical realisation, and discusses their application and limitations.

2. MEASUREMENT OF AIR CHANGE RATE

The direct measurement of air change rate involves the release and monitoring of a suitable non-toxic tracer gas (see Appendix 1) within the building. If the building is treated as a single enclosure in which tracer and ventilating air are perfectly mixed, then the generalised tracer mass balance equation (also known as the continuity equation) can be presented as

$$V \frac{dC}{dt} = Q[C_e - C(t)] + F \quad [2]$$

where

V	=	effective volume of enclosure, m ³
Q	=	air flow through enclosure, m ³ s ⁻¹
C _e	=	external concentration of tracer gas
C(t)	=	average internal concentration of tracer gas at time, t
F	=	production rate of tracer from all sources within enclosure

The assumption of perfect mixing is not usually achieved in practice, especially in larger buildings. Three major mixing problems can be identified:

Mixing of ventilation air into the enclosure

When fresh air enters an enclosure through a variety of openings, it may not disperse evenly throughout the space. In extreme cases the outdoor air can bypass the indoor air without mixing (short circuit) or it can propel the "old" air before it as it moves through the building (piston flow). The poor mixing of outdoor air can cause spatial variations of tracer gas concentration to occur. This problem may be overcome by monitoring the tracer gas at several locations within the building, but in some cases a multi-zone approach (see Section 3) may have to be taken.

Mixing of tracer gas into the enclosure

When gas is injected into a building it may take some time to mix with the internal air. If injection and sample points are located some distance apart, there will be a delay between the time gas is injected and the time the additional volume is reflected in the sampled concentration.

If, however, injection and sample points are close together, the tracer may not be allowed to disperse evenly in the air before being sampled. Injection problems are often reduced by artificially mixing the tracer gas with the air at the injection point. Care must be taken, however, to ensure that this process does not induce artificial flow conditions within the test space.

Mixing of air and tracer within the enclosure

It can be seen from Equation [2] that the volume used in the continuity equation is the effective volume. This is defined as the volume in which mixing occurs and it is not necessarily equivalent to the physical volume of the enclosure. The presence of cupboards and furniture can lead to the effective volume being smaller than the physical volume. These areas can often be readily identified and allowed for. Alternatively, their effect can be nullified, in the case of cupboards for example, by opening them to the main space. However, there may be other "dead" volumes, such as areas near the ceiling, isolated by stratification, which are more difficult to evaluate.

If there are attached spaces which can communicate with the measured enclosure, then the effective volume may be larger than the obvious physical volume. An example of this would be a suspended ceiling above a living

space. While it is often usual to assume that the effective volume will be approximately the same size as the physical volume, a careful examination of the building will lead to a more accurate evaluation of this parameter.

If due care and attention is given to the mixing problems outlined above, it is possible to experimentally evaluate air change rate from tracer gas concentration data. There are three distinct approaches to the solution of the continuity equation. These are considered in turn below.

2.1 Concentration Decay Method

The most straightforward method of solving the continuity equation is to make a one-time injection of tracer gas into the enclosure. Following the cessation of gas injection, assuming that the outdoor concentration of tracer gas is negligible, $C_e = 0$, and that there are no incidental sources of tracer within the building, $F = 0$, the continuity equation reduces to

$$V \frac{dC}{dt} = -QC(t) \quad [3]$$

Assuming that Q remains constant, Equation [3] can be solved for the tracer gas concentration, i.e.

$$C(t) = C_{(0)} e^{-\frac{Q}{V}t} \quad [4]$$

where $C_{(0)}$ = concentration of tracer gas at time, $t=0$
 $\frac{Q}{V}$ = N = air change rate, h^{-1}

Hence, under ideal conditions, the tracer gas concentration will exhibit an exponential decay with time. Therefore, if the time variation of the tracer concentration can be obtained, the air change rate, N , can be evaluated. The simplest method of performing this is to plot the concentration against elapsed time in hours on linear/logarithmic paper. The negative slope of the line is then equal to the air change rate expressed in units of h^{-1} .

There are essentially two methods of obtaining concentration data from test sites. Firstly there are techniques which require the equipment used to analyse the tracer concentration to be placed in the measurement building (site analysis). Secondly there are techniques, known as grab sampling, which involve obtaining samples of air in the building and removing them to another site for analysis.

2.1.1 Site Analysis

In its basic form, the site analysis technique for concentration decay measurements requires the following equipment:

- a. A tracer gas and some means of injecting it into the test space.
- b. A means of mixing the gas into the test space in order to obtain a uniform concentration.
- c. An analyser which can detect the tracer (see Appendix 1).
- d. A sampling system whereby a quantity of air can be introduced into the analyser.
- e. Some means of recording time.

The tracer gas is introduced to the test space and allowed to mix with the air. This mixing may be promoted by the use of paddles, electric fans or the ventilation system. After the mixing is complete, the tracer gas concentration is monitored over a period of time. Data can be taken by hand or by connecting the analyser to an x-t chart recorder. The data can then be analysed and a value for the air change rate obtained.

Even with associated measurements of wind speed and temperature, a single value of the air change rate provides little information regarding the ventilation behaviour of a building. Ideally a series of measurements should be made, preferably under a range of climatic conditions. In order to ease this process, several refinements can be made to the basic system. The gas injection process can be automated so that once the concentration has reached a certain minimum level, a further amount of tracer is injected into the test space (Grot et al [1981]). This allows many individual decays to be obtained. If more than one sample point is being used, then automatic switching between locations can be performed with solenoid valves.

For analysis purposes, the output of the analyser can be fed into a computer or data logger and this, together with the associated software, can calculate and output the air change rate directly. This computer could also be used for the storage of wind and temperature data. Hence the dependence of N upon climatic parameters can be examined. The main advantage of this type of technique is the basic simplicity of the instrumentation and analysis, an important point being that only relative and not absolute tracer concentrations need be measured.

2.1.2 Grab Sampling

This technique requires no expensive analysis equipment to be used on 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 or plastic bottle has shown itself to be adequate for the purpose, (e.g. Harrje et al [1982]).

After an initial time lapse to enable a uniform concentration of tracer gas to be reached, the air in the space is sampled. This can be performed with a syringe, bottle or bag. A sample taken in this manner is intended to give an instantaneous value of the tracer concentration at that time, hence the actual time taken to fill the container should be as short as possible. After further periods of time, more samples can be taken. A minimum of two samples are required to evaluate the decay but often more are taken to ensure accuracy. The time interval between samples or the absolute time they were taken must also be recorded. Air samples are then shipped to the laboratory for analysis. Concentrations are determined, the decay plotted and the air change rate evaluated.

The main advantage of this technique is its simplicity. Because of the minimum amount of site equipment required, many buildings can be examined from a central analysis point. Also, as it is kept at one location, delicate analysis equipment is less likely to be damaged or go out of calibration. Disadvantages include not being able to obtain results until some time after the site data is taken, and the likelihood of unintentional errors caused by non-technical site operators.

2.2 Continuous Emission

A second approach to the solution of the continuity equation is to set the source term, not at zero but at some fixed value. Assuming that $C_e = 0$, the mass balance equation is given by

$$V \frac{dC}{dt} = -QC(t) + F \quad [5]$$

For a constant ventilation rate, N , and constant gas discharge rate, F , Equation [5] can be solved in terms of tracer gas concentration to give

$$C(t) = \frac{F}{NV} [1 - e^{-Nt}] \quad [6]$$

If N remains constant, a finite time is required for the concentration to reach equilibrium. This time is determined by the bracketed function in Equation [6]. Once the concentration has reached equilibrium, the air change rate is given by

$$N = \frac{F}{VC(t)} \quad [7]$$

Hence, if measurements of tracer gas flow rate and tracer gas concentration can be made, N may be evaluated. There are two distinct types of constant emission technique.

2.2.1 Site Analysis

The essentials of the experiment are similar to the decay method except that the gas is injected continuously over the measurement period. In order to aid mixing, the gas may be discharged into the air stream of a small fan. It is necessary to have some instrumentation which enables the mass flow rate of tracer to be kept at a known constant value. Prior to monitoring, it may be necessary to spend some time injecting gas into the test space in order that approximate equilibrium conditions may be reached.

Once the transient effect has become minimal, the air change rate becomes inversely proportional to the tracer gas concentration in the test space and N can be calculated from Equation [7]. If the air change rate alters, then the gas concentration should again be allowed to reach equilibrium before the value of N is evaluated. This type of measurement is usually performed with automated equipment. The tracer gas concentration is measured continuously or at short intervals. Thus with care, continuous measurement of the air change rate may be made.

The main disadvantage of this technique is that large amounts of tracer gas are required and a certain amount of time must be allowed to enable equilibrium conditions to be achieved.

2.2.2 Averaging Techniques

An alternative to having all the analysis equipment on site is to have only the gas injection and sampling systems in the building. These are called averaging techniques because their main function is to determine the longterm average air change rate of a building.

Gas is released at a constant rate into the test space. Several methods have been used for this ranging from gas cylinders with a needle valve, through airtight bags fitted with a peristaltic pump (Sherman et al [1981]), to totally passive sources which emit tracer through a porous plug (Dietz et al [1986]). Once approximate equilibrium conditions have been achieved, the air in the building can be sampled.

Slowly drawing air through a pump into an uncontaminated gas bag and collecting tracer using a solid adsorbent have both been used as sampling methods. After the required averaging time, the air or tracer samples are returned to a laboratory and the tracer gas concentration evaluated. The average air change rate can be evaluated from

$$\bar{N} \approx \frac{F}{V\bar{C}} \quad [8]$$

where \bar{N} = average air change rate over a given time period
 \bar{C} = average concentration over given time period

The approximation is given in Equation [8] because it can be shown that the reciprocal of an average concentration is close but not identical to the average of reciprocal concentrations. Similar to the grab sampling method for decay measurements, site equipment is simple and may be used by non-technical personnel. The obvious disadvantage to this is that no detailed information about the variation of air change rate is obtained.

2.3 Constant Concentration

The third technique reduces the continuity equation to its simplest form. If the concentration of tracer gas is held at a constant level, then there is no rate change in tracer. Hence

$$F - QC(t) = 0 \quad [9]$$

which can be solved to give

$$N = \frac{F}{VC(t)} \quad [10]$$

This is the same expression as for the constant emission method. However, the only variable quantity here is the tracer gas production rate. The air change rate is then directly proportional to the gas injection rate required to maintain the concentration.

A constant concentration of tracer gas can be maintained only by using sophisticated equipment (Bohac [1986]). The constant concentration system varies the rate of tracer injection to regulate the concentration in the enclosure. This is known as a closed loop operation. The system feeds back information about the measured concentration in the enclosure in order to

adjust the injection rate which maintains the concentration at the required level. The known injection rate is then used to evaluate the air change rate. Fully automated instrument packages incorporating a micro-computer have been designed for this purpose. Using these packages, the concentration can be kept constant in several zones of the test building thus enabling the air change rate of individual rooms to be evaluated.

Being automated, the systems are ideal for measuring air change rates over extended periods. The main drawback with these systems is cost and such sophisticated instrumentation may only be suitable for long-term research projects.

3. MEASUREMENT OF INTERZONAL AIR FLOWS

The continuity equation given in Section 2 assumes that the test space is a single, well mixed enclosure. Recently, attention has been turned to the way in which air flows between internal spaces of a building. Measurement of these interzonal air flows also uses tracer gas techniques. The structure under consideration is assumed to consist of a number of physical cells, in each of which air and tracer are perfectly mixed. There are n cells and the volume of the i 'th cell is V_i . A tracer mass balance equation can be developed for each cell. In this case, as well as the exchange with the environment, the tracer lost to, and gained from, each of the other cells must be taken into account. Assuming $C_e = 0$, the continuity equation for the i 'th cell is given by

$$V_i \frac{dC_i}{dt} = F_i + \left[\sum_{j=1}^n Q_{ji} C_j (1 - \delta_{ij}) \right] - \left[Q_{i0} C_i + \sum_{j=1}^n Q_{ij} C_i (1 - \delta_{ij}) \right] \quad [11]$$

where V_i = effective volume of cell, i .
 C_i = tracer gas concentration in cell, i , at time, t .
 F_i = production rate of tracer in cell, i .
 Q_{ij}/Q_{ji} = volume flow rate of air between cells i and j . Q_{ij} indicates flow from cell i to cell j , Q_{ij} and Q_{ji} are not necessarily equal.
 Q_{i0} = air flow from cell, i , to the environment.

The delta function is given as

$$\begin{aligned} \delta_{ij} &= 0, \text{ when } i \neq j \\ \delta_{ij} &= 1, \text{ when } i = j \end{aligned}$$

Since there is no net buildup of air in the building, the total air flow into a cell must equal the total flow out. From the conservation of mass of air, a second set of n equations can be developed, i.e.

Flow in = Flow out

$$Q_{0i} + \sum_{j=1}^n Q_{ji} (1 - \delta_{ij}) = Q_{i0} + \sum_{j=1}^n Q_{ij} (1 - \delta_{ij}) \quad [12]$$

The principle task here is to determine the interzonal air flows, Q_{ij} 's. There are $(n^2 - n)$ unknown Q_{ij} 's plus $2n$ unknown values of Q_{i0} and Q_{0j} , given a total of $(n^2 + n)$ unknown values of air flow. If the n equations of Equation [12] are used, then there are still n^2 unknown air flows with only the n equations of Equation [11] left to solve them. Therefore $(n-1)$ independent sets of equations similar to Equation [11] must be generated. This is usually performed by using n different tracer gases. Two multiple tracer gas systems are described below, each of which is based on a measurement technique already described in Section 2.

3.1 Multi-zone Decay Measurements

This technique is an extension of the single zone decay method described in Section 2.1. A total of n tracers are required to examine a building with n zones. The method has been tested in buildings with up to three zones and tracer gases are released, one to each zone (Irwin [1985]). Injection of the tracer gas can be performed using an airtight syringe. Alternatively it may be released directly from the cylinder by briefly opening the gas valve. After injection, the tracer gases are mixed using oscillating desk fans and sampling of the air tracer gas mixture is achieved by drawing air through polythene tubes. The analysis system must be able to evaluate the concentration of all tracer gases in all zones. Freons have been used as the tracer gases and the concentrations evaluated using an electron capture detector (see Appendix 1).

The instantaneous interzonal air flows can be calculated from a knowledge of the time variation of tracer gas concentrations. While providing highly detailed information about the ventilation behaviour of buildings, this method requires the use of complex equipment and sophisticated analysis techniques.

3.2 Multi-zone Constant Injection Measurements

This technique utilizes the tracer gas emitters and passive samplers mentioned in Section 2.2. A different tracer source is placed in each distinct zone. Tracer gas is injected at a constant rate and the time average concentration is measured by the samplers (Dietz [1986]). From these concentrations and the known emission rates of tracer, the average interzone air flows can be calculated.

4. MEASUREMENT OF AIR LEAKAGE

The measurement of air leakage requires the production of an artificial pressure difference across a building envelope or component. The volume flow rate through the test object is then determined as a function of the pressure differential. A primary role of this approach is to negate the influence of climatic parameters and characterise the building structure itself. Therefore the imposed pressures are generally much greater than those created by natural forces.

The functional relationship between the air flow through and pressure difference across a leakage path is frequently described by a Power Law of the form

$$Q = k(\Delta P)^n \quad \text{m}^3\text{s}^{-1} \quad [13]$$

where Q = flow rate, m^3s^{-1}
 ΔP = pressure difference, Pa
 k, n = flow coefficients

The flow coefficient, k , is related to the size of the opening and the exponent, n , characterises the type of flow. For laminar flow $n = 1.0$. For turbulent flow $n = 0.5$. Experimentally derived values of k and n uniquely define the air leakage characteristics of the test piece. Substitution into Equation [13] will enable the air flow at any given pressure difference to be evaluated. This type of information is invaluable with regard to the numerical modelling of the ventilation process. Pressure tests can be used to evaluate whole buildings or individual building components.

4.1 Whole Building Air Leakage

4.1.1 Small Buildings

The majority of measurements in this category have been performed in small residential buildings. By replacing an external door with a panel containing a variable flow rate fan, a pressure difference can be created across the building envelope. Initially a research tool, several "blower doors" are now available from commercial manufacturers. Air flow through the fan creates a uniform static pressure within the building. Internal and external pressure taps are made and a manometer is used to measure the pressure difference across the envelope. The volumetric flow rate through the fan must also be evaluated. The higher the flow required to produce a given pressure difference, the less airtight the building.

The air flow required to produce a given pressure difference under pressurization will not necessarily be identical to the flow required to produce the same pressure difference under

depressurization. This difference is due, in the main, to the fact that certain building elements can act as flap valves. 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. Hence, ideally, the fan and flow measuring mechanism must be reversible (Swedish Standard [1987]).

Wind round the building together with internal/external temperature differences produce natural pressure differences across the building envelope. These pressures superimpose themselves on the pressure difference generated by the fan. The stack effect will have little influence except in high rise buildings. Wind velocity produces a significant effect even in low rise buildings. The maximum error will occur at combinations of high wind velocity and low induced pressure difference.

These measurements can be performed in a relatively short time. Practical uses for these techniques include the 'before' and 'after' testing of retrofit measures and assessing whether buildings meet airtightness regulations.

4.1.2 A.C. Pressurization

A technique is available which enables building airtightness at small pressure differences to be measured directly and without interference from climatic forces. Called AC pressurization (Modera and Sherman [1985]), it differs from normal fan pressurization in that a piston is used to create a sinusoidal change in the internal volume of the building at a known amplitude and frequency. The airtightness of the building affects the pressure change including amplitude and phase in that building, due to the periodic volume change.

If the building envelope was a rigid and completely airtight structure, the change in pressure could be precisely determined from the building volume and the piston displacement. Therefore, any deviation from predicted pressure can be attributed to leakage through the envelope. If the volume change and pressure response is measured, then the air flow through the envelope can be calculated. The main advantage of this technique is that it operates at the pressures which actually drive infiltration, i.e., $-5 \text{ Pa} < \Delta P < 5 \text{ Pa}$. Its main disadvantage is that it does not permit the measurement of large, long leaks such as undampened chimneys or open windows.

4.1.3 Large Buildings

Theoretically there is no limit to the size of building which can be examined with normal fan 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. Trailer mounted fans, with flow

capacities in the range of $25 \text{ m}^3/\text{s}^{-1}$ have been used to examine volumes in the region of $50,000 \text{ m}^3$ (e.g. Shaw [1981]). Because of the cost of such 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 (Persily and Grot [1986]). This technique relies on the building possessing a suitable mechanical ventilation system which can be adjusted to meet the needs of the experiment. Essentially the supply fans are operated while all return and exhaust fans are turned off. All return dampers must be closed so that the air supplied to the building can only leave through the doors, windows and other leakage sites.

4.2 Component Air Leakage

The air leakage characteristics of individual building components can be evaluated either directly or indirectly. By selectively sealing different potential leakage paths during a whole building pressurization test, it is possible to determine the fraction of the total air leakage through different components of the building envelope. As the components will be generally sealed from the inside, it is preferable that an overpressure rather than an underpressure be created within the building. Pressurization will tend to force the seal onto the component while a negative pressure would tend to act against the seal making it less airtight.

Direct measurement of component leakage entails using an airtight chamber to cover the interior face of a window or door, supplying air to or exhausting air from the chamber at a rate required to maintain a specified pressure difference across the specimen, and measuring the resultant airflow through the specimen. The test can be made more accurate if the pressure in the rest of the room is balanced to that in the chamber, thus minimising unwanted air leakage through the chamber walls. Measurements of individual components enables an air leakage profile of a large building to be created.

A further method of component testing consists of using a laboratory test rig into which the specimens can be fitted. A pressure is created across the component and the flow rate through it is measured. This has the advantage that a large number of tests can be performed under similar conditions and the effects of climatic forces are nullified.

5. CONCLUSIONS

This account of measurement techniques is neither detailed nor exhaustive. Instead emphasis has been placed on giving an introductory overview of the spectrum of methods by which the air change rate, interzonal air flows and air leakage characteristics of buildings can be measured.

Tracer techniques range from one-off measurements of the air change rate using the decay method, through passive evaluation of average air change rate, to continuous measurements of air change rate involving sophisticated control and analysis methods. Interzonal air flows can be evaluated using multiple tracer techniques and relatively simple fan pressurization methods can be used to evaluate the air leakage characteristics of whole buildings and building components. The Air Infiltration and Ventilation Centre is currently preparing a full analysis of ventilation measurement techniques which will be published in the near future.

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APPENDIX 1

Tracer Gases and Analysers

The fundamental requirement of a gas used as a tracer is that its concentration must be measurable to a good order of accuracy, even when highly diluted. The tracer should be cheap and readily available as should the gas analysis equipment. For site measurements the instrumentation must be compact, robust and portable. The gases present in ordinary air should not affect the tracer gas analysis. The tracer gas should not normally be present in outdoor air thus allowing the external concentration to be assumed to be zero. There should be no natural source of tracer within the enclosure, hence the source terms in the continuity equation will consist solely of the tracer deliberately produced for the test.

The tracer, which should have a similar density to air, must not be absorbed by walls or furnishings, or decompose, or react with building surfaces or constituents of air. This ensures that all the tracer leaving the enclosure does so by the process of ventilation. For safety considerations the gas should be neither flammable nor explosive and, as experiments are often performed in occupied buildings, it should have no adverse health effects in the concentrations required for the tests.

No gas fulfils all the requirements given above. However, several gases are currently being widely used as tracers. These include sulphur hexafluoride, nitrous oxide, freons, perfluorocarbons and carbon dioxide.

The concentration of nitrous oxide or carbon dioxide is usually evaluated using an infra-red absorption analyser. Infra-red analysis makes use of the fact that many gases exhibit energy absorption characteristics in the infra-red portion of the electro-magnetic spectrum. The amount of infra-red energy absorbed varies from gas to gas and is dependent on the concentration of absorbing gas in a sample. Elemental gases which are composed of multiple similar atoms such as oxygen and nitrogen (which are the main constituents of air) do not absorb in the infra-red and, therefore, do not interfere with the detection of the tracer.

One method of performing this analysis is to pass two beams of infra-red radiation of equal intensity through an analysis cell and parallel reference cell respectively. The analysis cell contains a sample of air in which the tracer gas is present while the reference cell contains a non-absorbing reference gas. The difference in intensity between these two streams after passing through the cells is monitored and this provides a measure of the tracer gas concentration.

Some gases, for example sulphur hexafluoride, perfluorocarbons and freons, capture electrons. This property can be utilized to detect the concentration of some tracers. Electron capture detectors use a small radioactive source to generate a cloud of electrons in an ionisation chamber. When a pulsed voltage is applied across the chamber, a

current flows. A sample of gas is injected into the cell. If the sample contains a tracer which is electron capturing, then the number of electrons in the chamber is reduced. This in turn causes the current across the chamber to decrease. The reduction in current is proportionate to the tracer gas concentration. Atmospheric oxygen has electron capturing properties, so this type of detector is invariably used with a gas chromatograph upstream of the detector to separate the oxygen from the tracer gas.

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PAPER 2

MEASUREMENTS OF INFILTRATION AND AIR MOVEMENT IN
FIVE LARGE SINGLE-CELL BUILDINGS

G. V. LAWRENCE and J. R. WATERS

Department of Civil Engineering and Building
Coventry Polytechnic
Priory Street
Coventry CV1 5FB
U. K.

SYNOPSIS

A six channel, computer controlled, tracer gas detection system for the measurement of infiltration rates and air movement in large single-cell industrial buildings has been designed, constructed and calibrated. This has been used for over 50 sets of tracer decay measurements in five single-cell buildings ranging in size from 4000 to 31000 m³. The buildings included a sports hall, a vehicle maintenance depot, two factory workshops and an aircraft hanger. Infiltration rates and interzonal flows were derived from the tracer decay curves using methods based on multizone theory. The analysis method includes a specially developed, constrained least squares technique which gives both infiltration rate and internal flow rates.

The equipment and method of analysis are briefly described, and results for each data set presented. A comparison of infiltration rates, derived from interzonal flows and from averaged tracer decay data is also given. In addition examples are given of comparisons between measured decay curves and theoretical decay curves reconstructed from the measured flow rates. Finally inconsistencies in the data and the model are discussed, together with suggestions for improvements to the experimental technique and the method of analysis.

1. INTRODUCTION AND OBJECTIVES

Although modern industrial buildings are often equipped with sophisticated mechanical ventilation systems, many new ones and most existing ones still rely on a combination of natural ventilation, infiltration and localised extract fans for control of indoor temperature and air quality. As with any other type of building, the potential for energy saving by reducing infiltration must be balanced against the need to maintain air quality, and this balance should be evaluated if any building improvement actions are to be judged. Knowledge of infiltration rates and internal contaminant concentrations is of considerable value in determining the need for such action and its subsequent effectiveness. The significant characteristic of industrial buildings is that they consist of a small number of large spaces, or cells, within each of which there are likely to be strong spatial variations in the effective infiltration rate and in the distribution of contaminated air. Therefore it is necessary that a measurement system should be capable of yielding information not only on whole building infiltration rates but also on the internal air movement patterns which give rise to the spatial variations. Furthermore, the distribution of contaminant concentrations within industrial buildings is due as much to the industrial activity as to the design of the building. Any realistic assessment must therefore be based on measurements of the building in use.

The objective of the study was to develop equipment and a methodology which would enable measurements to be made on industrial buildings which would give values of whole building infiltration rates, and in addition information on air movement patterns within the building. As it was the intention to conduct measurements on buildings in use, acceptability to the building's occupants was an important consideration. A subsidiary objective, therefore, was that the technique should cause minimum disturbance to activities within the building, and that it should be possible to conduct measurements and produce the results within a short time span, say, less than a day. Clearly the complete determination of internal air movement patterns requires very detailed measurements, and this is incompatible with the aim of minimising disturbance to the occupant. The approach therefore has been to adopt procedures which are acceptable to building occupiers, and to determine the extent to which air infiltration rates and air movement patterns can be obtained from a practical number of measurements.

2. THE MEASUREMENT SYSTEM

A detailed description of the tracer gas measurement system has been given by Waters et.al.¹ The need to measure internal air movements imposes a limitation on the choice of tracer gas method. Methods which require some additional imposed stirring throughout the monitoring period will upset the internal air movements which are to be measured. Therefore the tracer decay method is to be preferred to the constant concentration or constant injection methods. Also it is necessary to use tracer gases which are unlikely to be present in industrial atmospheres, and which, because of the large volumes of such buildings, are detectable at low concentrations. Although there are advantages in using multiple tracer systems, especially where internal flows are to be measured, it was considered simpler to choose a single tracer, and to optimise the detection system for that tracer. Sulphur hexafluoride was chosen and has been found to be entirely satisfactory. The measurement system is therefore a tracer gas monitoring device, in which detection is achieved by six independent custom built gas chromatograph units. The use of six independent units permits rapid sampling from at least six sample points, and the use of pulse modulated electron capture detectors within the chromatographs provides both high sensitivity and good linearity over a wide range of tracer concentrations.

A comprehensive evaluation of the detector behaviour was carried out, from which it was possible to optimise the chromatograph parameters with respect to sulphur hexafluoride. Because the system uses six separate detector units, calibration is of particular importance. Therefore a special calibration rig was built, based on the accurate dilution of a sulphur hexafluoride/air mixture. A standard mixture is used at intervals during actual measurements to give a check on the relative performance of the six units.

The whole system, complete with calibration gases, data acquisition unit, and control computer, is mounted in a small covered trailer, which in most cases may be parked within the building under investigation.

3. MEASUREMENT METHODOLOGY

The theoretical basis of the methodology that has been adopted is that the large volume of air enclosed by a single-cell building can be notionally subdivided, or discretised, by imaginary boundaries into a large number of small volumes, or zones. Although the boundaries between the zones are hypothetical, in practice many single-cell buildings contain partitions screens or furniture which give physical reality to some of the boundaries. If each zone is small enough the distribution of contaminants, including the tracer gas, within the zone will be sufficiently uniform for the air in the zone to be considered well mixed. The system is then identical to the usual multizone model² of air flow within a building, and the interzone flow rates will be a measure of the magnitude and direction of the air movement within the complete volume. A detailed theoretical analysis of single gas tracer decay in a multizone model has been carried out by Waters and Simons³. This showed that the best seeding strategy is to seed a single zone, and that this should be the zone associated with the smallest component of the dominant eigenvector in the solution of the multizone equations. This is also the zone which, as the transients die out and the process approaches a steady decay, exhibits the lowest value of the tracer concentration. It can therefore be identified by a preliminary measurement. If this is not convenient, it can also be identified as the zone receiving the largest inflow of fresh air, and is therefore likely to be the most exposed zone on the windward side of the building. Fortunately, it is almost as satisfactory to seed any single zone, provided that in the subsequent measurements it is possible to detect tracer gas in all zones in the system. Nevertheless the analysis also revealed two possible difficulties. One occurs with particular flow patterns, which give rise to repeated eigenvalues in the multizone solution. The other occurs when there are certain kinds of symmetry in the interzonal flows, which, when a particular zone is seeded, leads to decay curves in which the concentration in one zone is a constant ratio of the concentration in another zone. The latter leads to linear dependency in the solution for the inter-zone flows, which because of experimental scatter in the data, manifests itself as ill-conditioning. Seeding strategy had to take account of these possible difficulties. The actual measurement procedure is conventional. The trailer is parked either within the building, or immediately outside, so that it is only necessary to run tubing from the trailer to the sample points. The position of the sample points is chosen according to building geometry and the extent of internal obstructions. In open buildings with few obstructions, the building is divided into imaginary zones of approximately equal volume, with a sample point at the centre of

each zone. Where internal obstructions are significant, sample points are placed to represent the spaces that obstructions delineate. However, in occupied buildings, it is often necessary to displace the sample point from the desired position to avoid interference with building activities. The sampling heads themselves consist of a small cylindrical manifold from which radiate nine 1 cm lengths of copper tubing, in the manner of the spokes of a wheel. At each sample point, therefore, air is collected from nine equally spaced points around the circumference of a 2 m circle. This provides some spatial integration of the sample collection within each zone. Pure sulphur hexafluoride is injected into a single zone on the windward side of the building, with stirring during the injection process, and the tracer decay is followed for between one and two hours.

4. MEASUREMENT PROGRAMME

A total of 58 sets of measurements have been obtained, distributed approximately equally between the following five buildings:

1. Abbey School Sports Hall, Kenilworth, Volume 4220 m³
2. Courtaulds Engineering Workshop, Coventry, Volume 14370 m³
3. Courtaulds Pattern Making Shop, Coventry, Volume 6420 m³
4. Hangar 5, Coventry Airport, Volume 31300 m³
5. British Gas Maintenance Depot, Birmingham, Volume 31020 m³

Except for the Sports Hall, all the buildings were in use during the measurements; in Hangar 5 all measurements were taken with the aircraft doors closed. In all cases, six sampling points were used, which were positioned to represent equal volumes, except where internal obstructions were significant, in which case they were positioned to represent the spaces that the obstructions created.

All the buildings were naturally ventilated, but Courtaulds Pattern Making Shop and British Gas Maintenance Depot had fume extract systems at strategic positions. Also, the British Gas building had an experimental mechanical ventilation and heat recovery system which was switched off for all but three of the measurements.

5. ANALYSIS OF RESULTS

Results for each measurement set were processed in two ways:

1. Readings for all six sample points were averaged to give a single overall average tracer concentration for the whole building. The decay of the average concentration was used to obtain the fresh air infiltration rate of the whole building.
2. Using multizone theory, a constrained least squares technique was used to determine the complete set of interzone flow rates. The fresh air infiltration rate of the whole building was found by summing the flows between individual zones and the outside.

For both methods of analysis, the data set for each run was split into sections, and each section analysed separately. These sections were:

1. the first third of the data in the time series
2. the second third
3. the last third
4. the first two thirds
5. the last two thirds
6. the whole data set.

Thus for each method of analysis there were six sets of results for each run.

The justification for the first method of analysis follows from the standard solution to the multizone problem. If $\underline{c}(t)$ is the vector representing the tracer concentration in the n zones of a building, then

$$\underline{c}(t) = \sum_{k=1}^n a_k \underline{x}_k e^{\lambda_k t}$$

where λ_k and \underline{x}_k are the eigenvalues and their associated eigenvectors of the solution, and the a_k are the constants associated with the initial condition (i.e. the seeding strategy). The average concentration $\bar{c}(t)$ of the n zones is, if the zones are of equal size, given by

$$\begin{aligned} \bar{c}(t) &= \frac{1}{n} \left[a_1 (x_{11} + x_{12} + \dots) e^{\lambda_1 t} + a_2 (x_{21} + x_{22} + \dots) e^{\lambda_2 t} + \dots \right] \\ &= \frac{1}{n} \sum_{k=1}^n A_k e^{\lambda_k t} \end{aligned}$$

where $A_k = a_k (x_{k1} + x_{k2} + \dots)$.

The decay of the average concentration is therefore governed by the same set of eigenvalues. Now Waters and Simons³ have demonstrated that as the internal flow rates increase, the dominant eigenvalue decreases, and approaches the value that would apply if the whole building were a single fully mixed zone. At the same time the other eigenvalues also get smaller, approaching in the limit $-\infty$. The implications of this for the decay of the average concentration, $\bar{c}(t)$, are shown in figure 1, in which the natural logarithm of $\bar{c}(t)$ is plotted against time. Now the gradient of the decay curve for the fully mixed case gives the whole building infiltration rate.

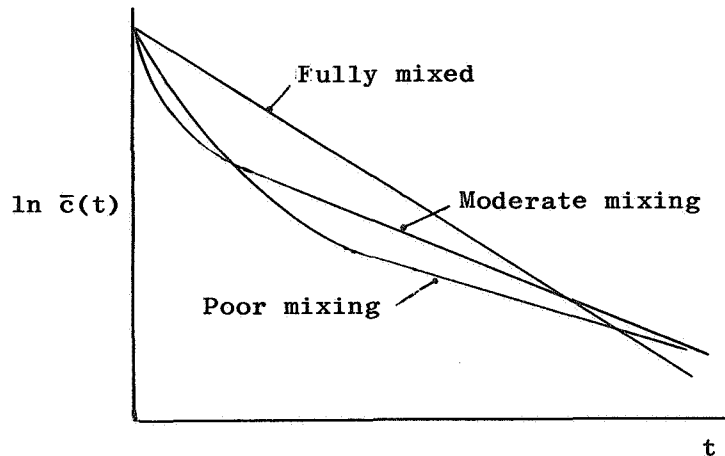


Figure 1. The effect of mixing on the decay of $\bar{c}(t)$

It can be seen therefore that in all other cases the gradient from the early part of the decay will over-estimate the whole building ventilation rate, whereas the gradient from the later stages where the dominant eigenvalue is in control will under-estimate it. These two values must give the limits within which the whole building infiltration lies, and the average gradient of the whole data set will lie close to the true value.

The solution for the individual flows is found by direct substitution of measured tracer concentrations and concentration gradients in the fundamental equations. However, the problem is first reduced by determining, from building geometry and from examination of the decay curves, which of the interzonal flows, F_{ij} are zero. Secondly, constraints are applied. Obviously we must have all $F_{ij} \geq 0$, but in addition examination of the decay curves in the seeded zone and zones adjacent to it, at times close to the start of the process, provides the possibility of including further constraints. If i is the seeded zone, and j a zone with a flow connection to i , then it may be shown (ref.3) that at time $t = 0$,

$$\sum_{j=0}^n F_{ji} = \sum_{j=0}^n F_{ij} = -v_i \frac{\dot{c}_i(0)}{c_i(0)}$$

and $F_{ij} \leq v_j \frac{\dot{c}_j(0)}{c_i(0)}$

where v_i is the volume of zone i . Using the method described by Lawson and Hanson⁴, these constraints are applied to the least squares solution.

6. PRESENTATION AND DISCUSSION OF RESULTS

Tables 1 to 5 inclusive give the results for the whole building infiltration rate, calculated by both methods of analysis. For each run, the first row, marked AC, gives values computed from the average concentration, and the second row, marked IF, gives values computed from the interzonal flows. The last column gives the best value of the infiltration rate, which is assumed to be that given by the whole data set, and the range, which is the difference between the best value and the extreme values expressed as a percentage. Each table also includes a plan diagram of the building, with the interzonal flows computed from one of the runs superimposed.

For each run, the infiltration rates obtained from the average concentration vary according to the data subset from which they have been calculated in the expected manner. With very few exceptions, the highest value comes from the first third of data and lowest from the final third. The range is often much greater on the positive side than the negative side. This again is to be expected, because the early decay rate is primarily a function of the flow rates out of the seeded zone, which may be very large. It is likely, therefore, that a large value on the positive side over-estimates the probable error in the best value.

If the data set were free from experimental error, and if the assumptions of multizone theory were valid in these buildings, the infiltration rates computed from interzone flows would be the same whichever data subset was used in the analysis. Neither condition is true, and the results often show marked variability. Comparing the infiltration rates from the interzone flows with the 'best value' from the average concentration suggests that where agreement is good, variability is low, and vice versa. For example, taking as a measure of the variability of the six IF values in any run the ratio of the standard deviation to the mean, the following three runs illustrate the trend:

Building 1	Best Value	IF Value	SD/mean
Run 13	4.15 ach	1.09 ach	0.61

Building 3 Run 36	Best Value 2.69 ach	IF Value 3.05 ach	SD/mean 0.43
Building 3 Run 39	Best Value 2.57 ach	IF Value 2.48 ach	SD/mean 0.30

One possible explanation for the variability is that the length of the data sets was determined arbitrarily by the time available for each run. Waters and Simons³ demonstrated that for single zone seeding the decay process is close to uniformity at a time of two time constants from the start, where the time constant is defined as the reciprocal of the dominant eigenvalue. The inclusion of data beyond this time may be weighting the least squares solution towards linear dependency. Some of the results were recalculated with the data set restricted to two time constants, where the time constant was assumed to be given with sufficient accuracy by the reciprocal of the 'best value' infiltration rate. In table 6 run 13

TABLE 6

EFFECT OF RESTRICTING DATA SET TO TWO TIME CONSTANTS

	Infiltration rate, ach, from interzonal flows						SD/means
	Data Subset						
	1	2	3	4	5	6	
Run 13							
Full data	0.72	0.83	0.48	0.63	2.13	1.09	0.61
2t	1.48	0.19	0.69	3.98	0.03	0.84	1.21
Run 36							
Full data	5.71	4.10	1.88	3.35	1.97	3.05	0.43
2t	3.09	3.24	4.05	3.72	1.39	1.58	0.39

the variability and agreement with the 'best value' are worse, and for run 36 there is no improvement. The individual interzonal flows also show considerable variation between the solutions from different data subsets, and again there is a tendency for the variability to be less where agreement for the infiltration rates is good. The extreme sensitivity of the interzonal flows to the manner in which the data is selected and processed has also been noted by Afonso et.al⁵ who also used a single tracer gas. Nevertheless, they were able to get reasonable agreement with independently measured values of the interzonal flows, but it is of interest to note that they were using only 2 zones in an experimental set-up which was designed to match the assumptions of the multizone model.

As a further indicator of the quality of the interzonal flow results, theoretical decay curves were computed from the flows, and compared with the original measured curves. This is a severe test, and where the flow results are in doubt because the whole building infiltration rates are inconsistent, the reconstituted curves bear little resemblance to the measured originals. However, where there is some measure of consistency in the infiltration

rates, the two sets of curves can show at least a reasonable similarity. Figs 2-4 show as an example run 36. This run also illustrates one of the major reasons for the difficulties in obtaining good matching. It can be seen from the measured curve that there is a time lag effect, shown by tracer concentration peaks in standing above the general trend of the decay. This is not possible on the basis of the normal multizone model.

7. CONCLUSIONS

The results for infiltration rate computed from the average concentration appear to be sufficiently consistent to be considered reliable, and show that it is comparatively easy to obtain reasonable values for buildings in the size range considered without recourse to elaborate technique or analysis. The values for the infiltration rates were in most cases surprisingly high, but all these buildings were very leaky, with large badly fitting doors, which in some cases were left open during normal working.

The results for interzone flows were always plausible, but this was due to the imposition of constraints on the solution technique. In most cases, lack of consistency and poor agreement with the infiltration rates obtained from the averaged data, suggest that at the present stage of development the interzone results are too unreliable to be useful. The most probable explanations for the poor results are:

1. The size of the hypothetical zones was too large to give adequate discretisation of the internal volume of these buildings. The choice of six channels for the measurement system was dictated partly by experience from a preceding pilot study and partly by available resources. Thus, in these buildings, each zone was large enough for there to be spatial variations within it.
2. The 2 metre diameter sampling head used in each zone was small in relation to the size of each zone, and therefore may not have given a reasonable measure of the average tracer concentration in that zone.
3. Because artificial mixing of the air in these buildings has been deliberately avoided, the normal multizone model is not strictly applicable, even with discretisation into small zones.

Each of these problems can be overcome to some degree. The first two could be ameliorated by increasing the number of zones, either by adding extra channels to the equipment, or by multiplexing the existing channels. At the same time, the sampling arrangement could be altered to give a more representative value of the concentration in each zone. Unfortunately, both of these possible courses of action would increase the disturbance caused to the building occupier.

The third problem has been approached by reconsidering the air flow model of the building. Instead of considering the air volume as an assembly of perfectly mixed zones, it is more realistic to consider it as a combination of pockets of good mixing (or zones) linked by air streams in which the air flow is predominantly in one direction. These latter approximate to ducts. An alternative model is therefore, an assembly of perfectly mixed zones linked by ducts in which the flow is unidirectional. The solution of this alternative model is much more difficult. Nevertheless a solution has been obtained for the case of two zones linked by two ducts (reference 6). The most significant feature of the solution is that the decay curves can exhibit the time delays and oscillatory behaviour which has often been observed in our measured decay curves. It would be very interesting to solve a model of six zones connected by unidirectional flow ducts, but this has not yet been achieved.

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Table 1

BUILDING 1 : ABBEY SCHOOL SPORTS HALL

Run No	Wind Vel m/s	Analysis Method	Whole Building Infiltration Rate (ach)						Best Value & Range %	
			Data Subset							
			1	2	3	4	5	6		
12	5.1	AC	4.95	4.04	3.59	4.24	3.73	3.83	3.83 +29 -6	
		IF	5.70	6.71	80.8	2.08	28.4	14.1		
13	5.7	AC	5.56	4.25	3.83	4.60	3.97	4.15	4.15 +34 -8	
		IF	0.72	0.83	0.48	0.63	2.13	1.09		
14	6.9	AC	5.39	4.78	4.35	4.91	4.49	4.56	4.56 +18 -5	
		IF	1.89	10.3	0.86	2.45	3.42	1.68		
16	5.1	AC	3.64	3.69	3.53	3.68	3.58	3.58	3.58 +3 -1	
		IF	1.60	4.99	293	0.33	4.27	4.57		
17	3.1	AC	4.23	4.41	3.99	4.37	4.12	4.13	4.13 +7 -3	
		IF	3.69	0.77	1.17	1.14	2.46	1.93		
18	5.1	AC	3.60	3.13	3.28	3.24	3.23	3.26	3.26 +10 -14	
		IF	0.98	1.27	2.85	1.86	0.45	2.31		
19	6.2	AC	4.66	3.32	2.95	3.61	3.07	3.20	3.20 +46 -8	
		IF	4.06	3.50	14.8	2.77	9.07	2.25		

Interzone Flows ms^{-1} , Run 13 Data Subset 6

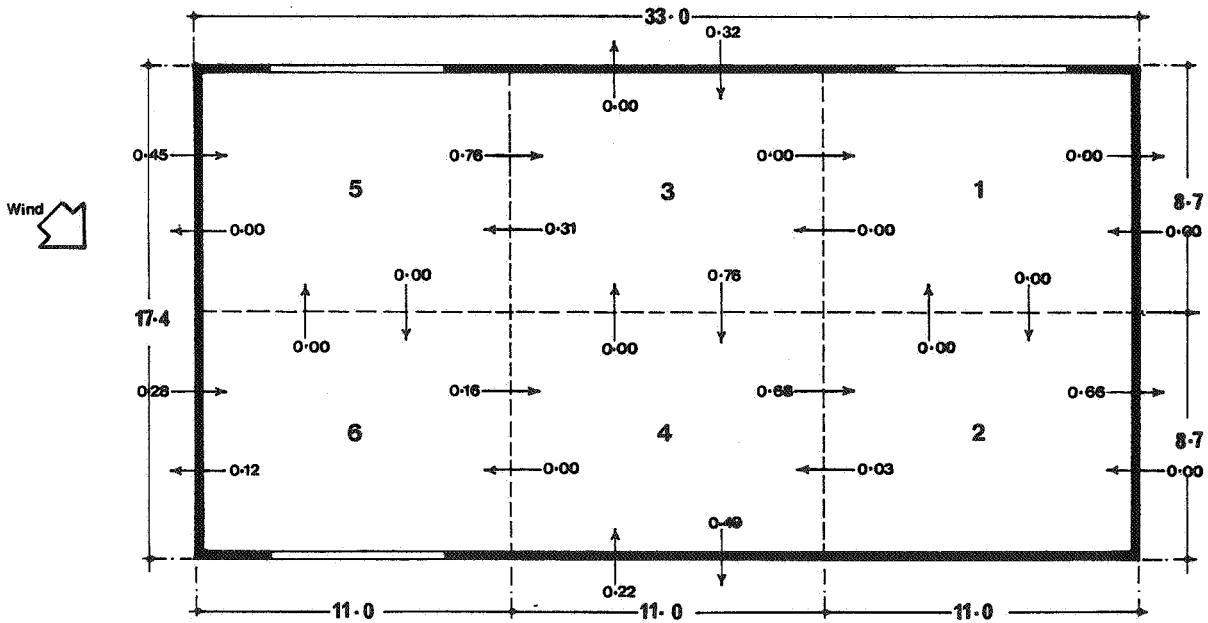


Table 2

BUILDING 2 : COVENTRY AIRPORT HANGER 5

Run No	Wind Vel m/s	Analysis Method	Whole Building Infiltration Rate (ach)						Best Value & Range %		
			Data Subset								
			1	2	3	4	5	6			
21	6.2	AC	9.27	6.33	4.97	6.81	5.36	5.57	5.57	+66	-11
		IF	9.86	3.11	6.02	7.91	2.94	7.10			
22	7.2	AC	5.69	5.84	5.70	5.81	5.74	5.74	5.74	+2	-1
		IF	5.35	2.17	3.95	3.16	4.04	6.53			
23	6.7	AC	5.64	5.02	4.69	5.13	4.79	4.84	4.84	+17	-3
		IF	3.72	1.26	1.06	4.66	7.34	3.62			
24	6.7	AC	5.24	4.20	3.34	4.42	3.61	3.73	3.73	+40	-10
		IF	7.14	3.24	54.1	3.11	10.8	11.7			
26	5.1	AC	4.17	3.34	2.58	3.52	2.81	2.92	2.92	+43	-12
		IF	4.23	4.85	30.2	2.48	57.2	3.91			
27	3.6	AC	5.84	4.66	3.94	4.89	4.16	4.27	4.27	+37	-8
		IF	9.48	10.1	16.8	6.08	5.21	10.6			
28	5.1	AC	5.24	4.16	3.58	4.33	3.74	3.84	3.84	+36	-7
		IF	1.95	1.58	2.60	2.47	5.62	3.14			
30	3.6	AC	6.98	3.72	3.00	4.41	3.22	3.51	3.51	+99	-15
		IF	3.82	2.11	0.47	1.48	2.37	1.19			

Interzone Flows ms^{-1} , Run 28 Data Subset 6

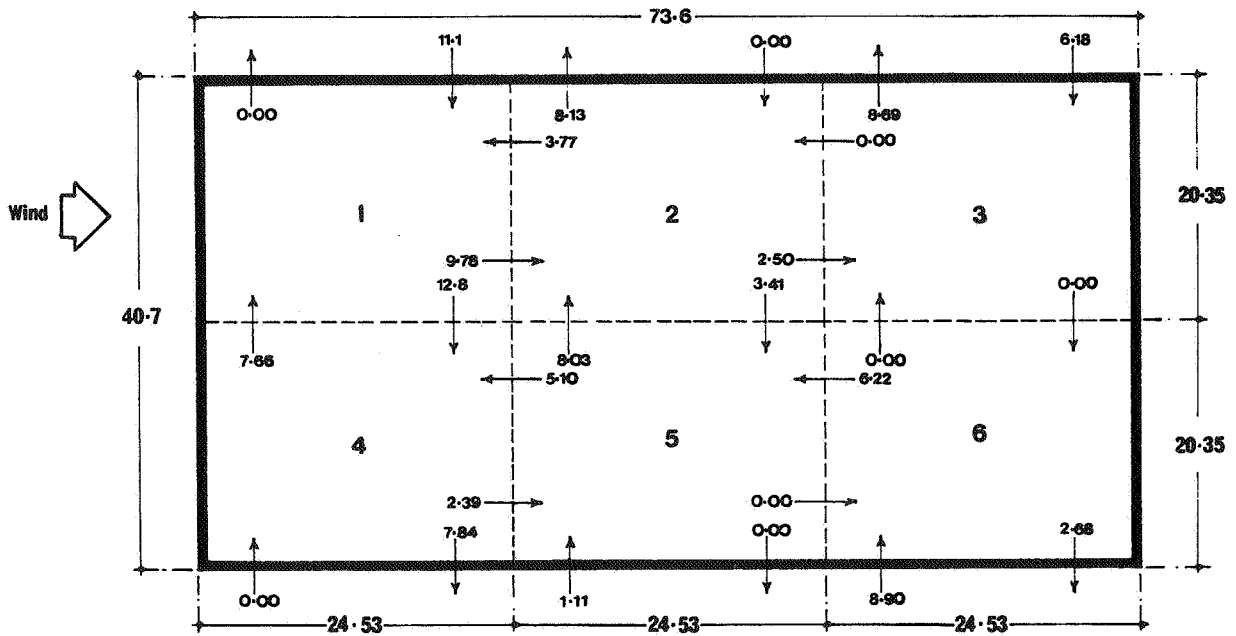


Table 3

BUILDING 3 : COURTAULDS FITTING SHOP

Run No	Wind Vel m/s	Analysis Method	Whole Building Infiltration Rate (ach)						Best Value & Range %
			1	2	Data Subset		5	6	
31	6.7	AC	5.05	3.10	2.31	3.47	2.55	2.71	2.71 +86 -15
		IF	4.83	8.66	18.9	13.2	11.4	6.49	
32	4.1	AC	4.24	2.72	2.15	3.00	2.32	2.44	2.44 +74 -5
		IF	3.89	2.58	1.01	2.97	3.33	1.67	
34	2.6	AC	4.36	2.85	2.19	3.21	2.40	2.58	2.58 +69 -15
		IF	1.43	0.88	1.78	2.65	0.75	2.60	
35	1.5	AC	4.27	2.64	2.04	2.95	2.22	2.36	2.36 +81 -14
		IF	2.10	2.11	2.01	4.94	3.95	2.52	
36	1.5	AC	4.75	3.02	2.34	3.34	2.54	2.69	2.69 +77 -13
		IF	5.71	4.10	1.88	3.35	1.97	3.05	
38	4.1	AC	3.72	2.48	1.91	2.70	2.08	2.18	2.18 +71 -5
		IF	3.61	0.20	1.40	3.68	1.31	3.83	
39	3.1	AC	4.53	2.88	2.22	3.21	2.42	2.57	2.57 +76 -14
		IF	2.16	2.47	1.88	1.51	0.99	2.48	

Interzone Flows ms^{-1} , Run 34 Data Subset 6

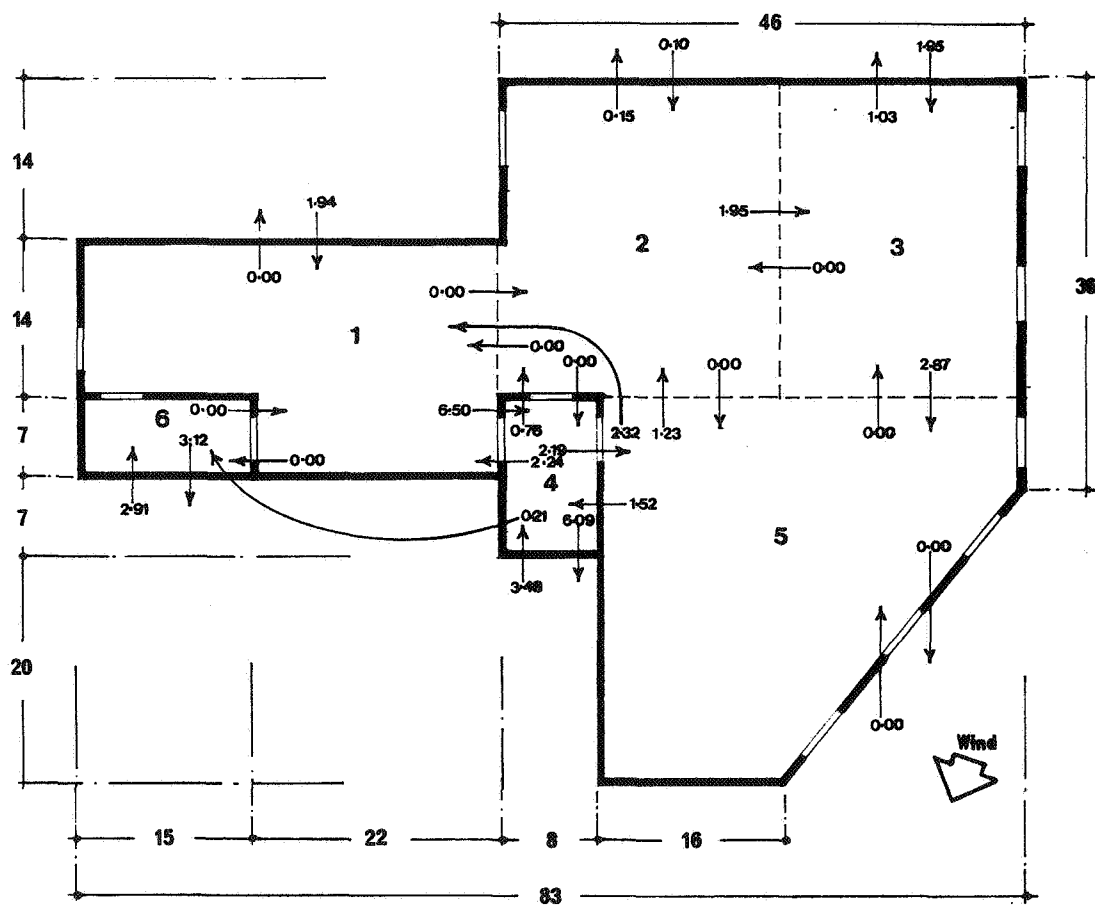


Table 4

BUILDING 4 : COURTAULDS PATTERN SHOP

Run No	Wind Vel m/s	Analysis Method	Whole Building Infiltration Rate (ach)						Best Value & Range %
			Data Subset						
			1	2	3	4	5	6	
41	6.2	AC	2.54	1.91	1.63	2.01	1.71	1.75	1.75 +45 -7
		IF	5.70	1.05	1.33	2.93	0.96	1.64	
42	7.2	AC	2.38	1.75	2.10	1.84	2.00	2.01	2.01 +18 -13
		IF	2.50	1.74	4.75	1.06	1.34	3.44	
43	1.5	AC	2.09	1.69	1.35	1.76	1.45	1.48	1.48 +41 -9
		IF	1.04	2.90	2.99	2.71	3.05	0.80	
45	5.7	AC	1.93	1.47	1.61	1.55	1.57	1.59	1.59 +21 -8
		IF	2.04	3.81	1.52	2.05	2.27	3.18	
46	5.7	AC	2.37	1.90	1.70	1.99	1.76	1.80	1.80 +32 -6
		IF	0.91	1.16	3.22	0.93	1.45	1.36	
47	10	AC	2.84	2.23	2.08	2.35	2.13	2.17	2.17 +31 -4
		IF	0.72	1.53	2.29	2.94	2.01	1.30	
48	6.2	AC	3.61	2.70	3.11	2.91	2.98	3.03	3.03 +19 -11
		IF	7.83	1.41	6.36	1.89	4.44	3.38	
49	8.2	AC	2.65	2.09	1.95	2.19	1.99	2.03	2.03 +31 -4
		IF	3.10	1.26	1.43	1.29	3.47	0.88	
50	9.3	AC	2.94	2.72	2.69	2.76	2.70	2.72	2.72 +8 -1
		IF	0.49	1.42	3.34	1.01	0.68	0.29	

Interzone Flows ms^{-1} , Run 49 Data Subset 6

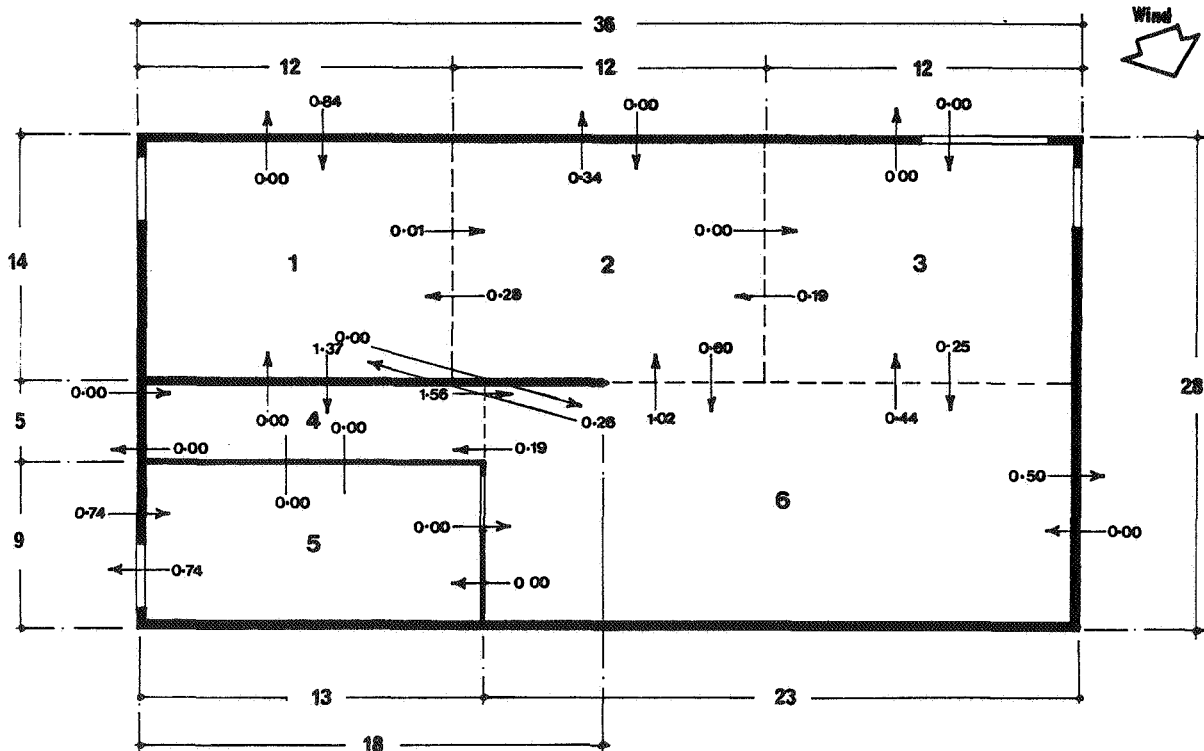
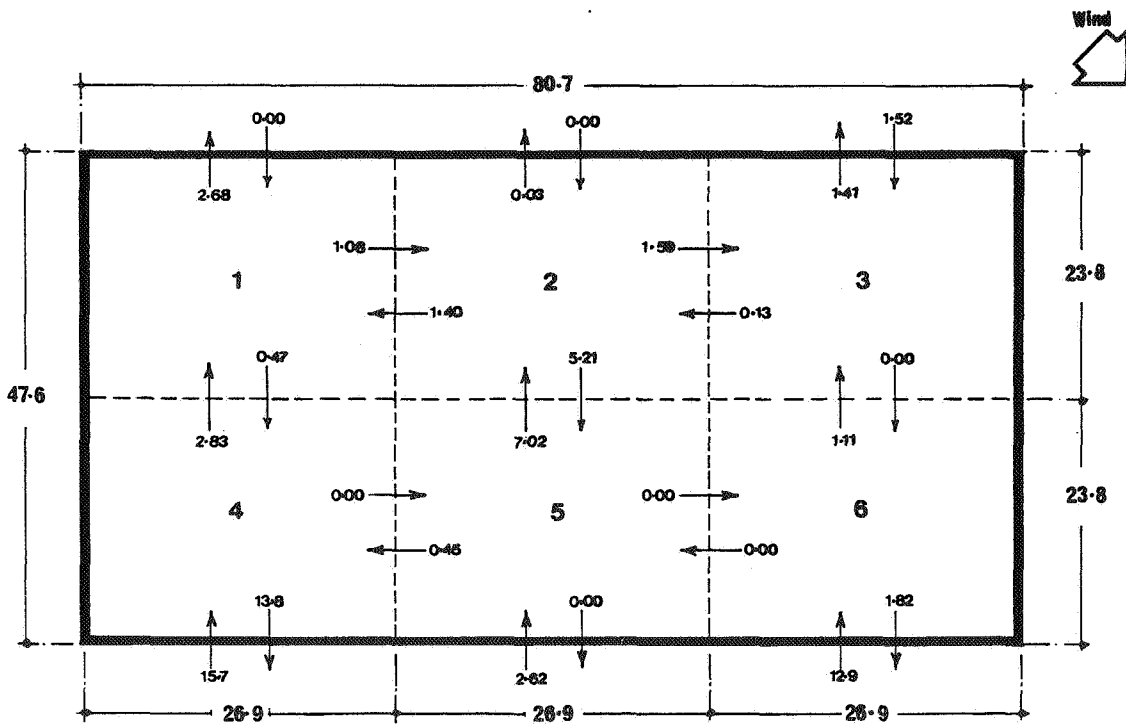


Table 5

BUILDING 5 : BRITISH GAS MAINTAINANCE DEPOT

Run No	Wind Vel m/s	Analysis Method	Whole Building Infiltration Rate (ach)						Best Value & Range %
			1	2	Data Subset		5	6	
63	5.1	AC	3.54	2.54	2.83	2.77	2.74	2.81	2.81 +26 -10
		IF	3.65	4.05	6.08	2.01	4.65	2.20	
65	3.6	AC	3.14	2.47	2.46	2.60	2.46	2.51	2.51 +25 -2
		IF	0.53	1.00	2.12	2.26	1.66	0.91	
66	2.6	AC	6.42	4.29	3.65	4.79	3.86	4.09	4.09 +57 -11
		IF	1.75	1.38	0.81	0.46	1.78	0.80	
67	2.6	AC	4.29	3.26	2.96	3.50	3.06	3.17	3.17 +35 -7
		IF	1.40	4.04	4.33	2.98	4.94	3.76	
68	3.6	AC	9.29	6.07	4.91	6.82	5.28	5.63	5.63 +65 -13
		IF	6.55	2.89	5.14	2.33	4.94	4.36	
69	4.6	AC	2.97	2.59	2.83	2.46	2.76	2.69	2.69 +10 -9
		IF	0.88	1.97	1.28	0.61	2.31	1.17	
71	2.6	AC	4.47	3.85	3.36	4.00	3.52	3.61	3.61 +24 -7
		IF	0.54	2.16	3.71	0.99	2.15	0.75	
73	2.6	AC	2.92	2.52	2.56	2.61	2.55	2.58	2.58 +13 -2
		IF	0.96	2.85	1.14	0.54	1.05	1.21	
74	2.1	AC	3.44	2.73	2.81	2.94	2.78	2.87	2.87 +20 -5
		IF	6.05	3.06	4.33	3.42	5.75	4.19	

Interzone Flows ms^{-1} , Run 67 Data Subset 6



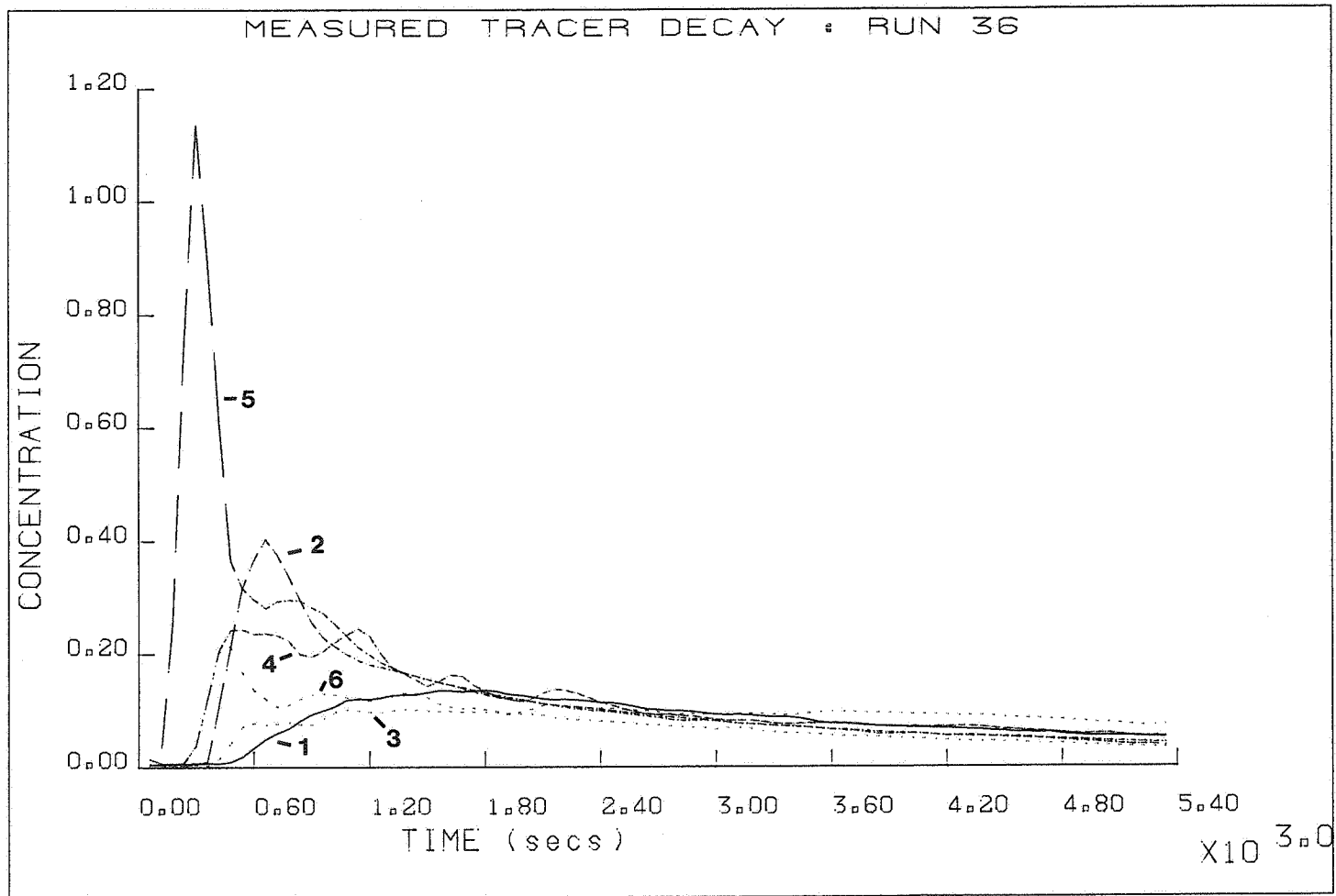


Figure 2. Measured tracer decay in Building 3, run 36

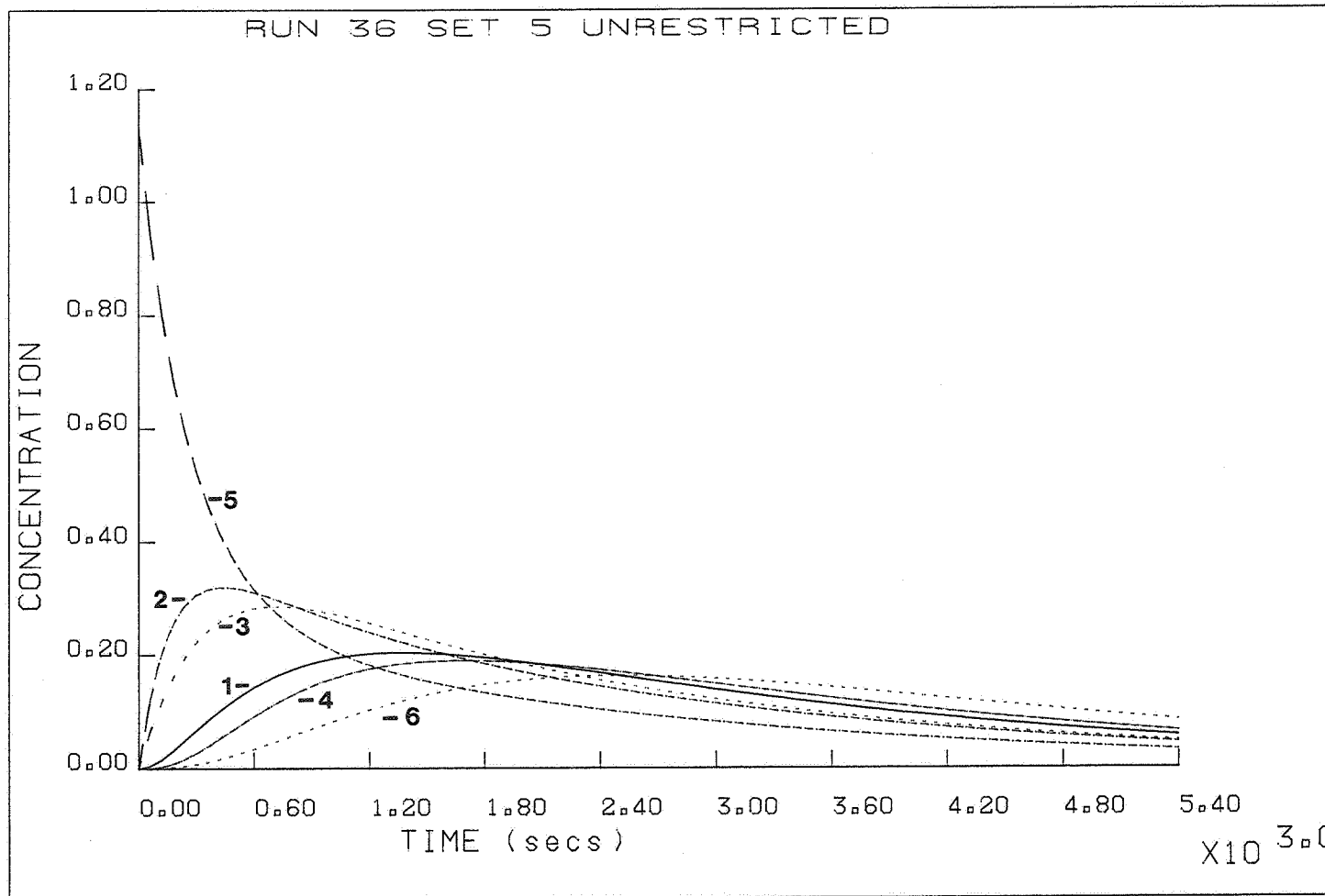


Figure 3. Computed tracer decay in Building 3, run 36
Interzonal flows obtained from data subset 5 of full data

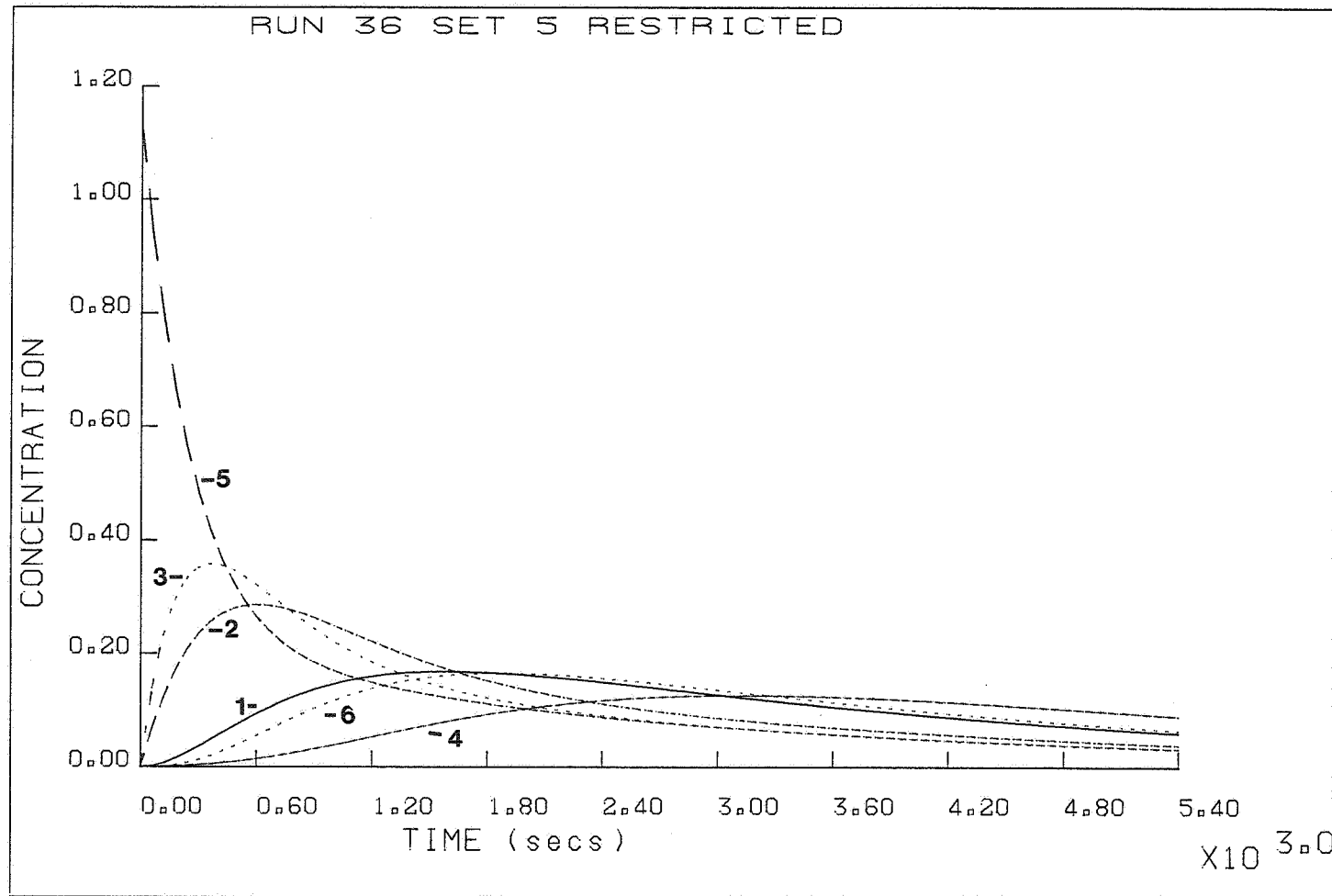


Figure 4. Computed tracer decay in Building 3, run 36
Interzonal flows obtained from data subset 5 of
data restricted to 2 time constants

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PAPER 3

DEVELOPMENTS IN A MULTI-TRACER GAS SYSTEM AND MEASUREMENTS USING
PORTABLE SF₆ EQUIPMENT.

S B RIFFAT, M EID AND J LITTLER

Research in Building Group
The Polytechnic of Central London
35 Marylebone Road
London
NW1 5LS
UK

ABSTRACT

In this paper we describe the development of a multi-tracer gas system for measuring interzonal air movement in buildings. The system consists of simple and stand-alone gas injectors and sampling units. The injectors are capable of releasing up to four perfluorocarbon tracer gases in different parts of a building. Following tracer gas injection and mixing, small samples of air are collected using automatic sampling units. Each unit consists of a 16-position valve and a group of removable stainless steel tubes packed with solid absorbent. Samples may be taken simultaneously at up to four points in space and up to 16 points in time. These samples are then stored for subsequent analysis in the laboratory using an automatic thermal desorber and gas chromatograph.

In the second part of the paper, the portable sulphur hexafluoride (SF_6) system is described. The system incorporates an electron capture detector gas chromatograph and operates automatically using a BBC microcomputer. Using this system the air change rates were measured in a number of recently constructed houses in the Milton Keynes area, UK. The test data of various measurements are presented together with an analysis of the results.

1. INTRODUCTION

One aspect of energy conservation attracting attention at present is the reduction of heat losses in buildings derived from poor thermal insulation and high air infiltration rates. As a result a large number of superinsulated houses are being built in Scandinavia, North America and recently in the UK¹. These houses are constructed in such a way that air leakage through cracks and openings in their envelopes no longer serve as a source of ventilation and so mechanical ventilation systems are required. Inadequate air change rates give rise to an increase in indoor air contaminants (eg., formaldehyde, nitrogen dioxide and moisture) which have an important influence on the health and comfort of the building's occupants. Research is therefore required to evaluate the extent of air ventilation and dispersion of interior contaminants so that the optimum compromise between energy consumption and sufficient air change to maintain a healthy environment is achieved.

The air tightness of buildings can be examined by pressurisation using blower doors. Unfortunately, this technique is unable to provide information on air infiltration in a building under natural climatic conditions. As an alternative, tracer gas techniques may be used for measuring air change rates in buildings. Reviews of various tracer gases and measuring techniques have been made by Harrje et al², Sherman et al³, and Lagus and Persily⁴. Until recently, measurement of air movement has usually involved the assumption that the building is a single uniformly mixed zone. However, multizonal measurements are essential if movement of indoor air contaminants and energy transfer among various parts of the building is to be accurately represented. The measurement of interzonal air flows in buildings, such as hospitals, is important as the transport of odours and bacteria between various ward units must be kept to minimum⁵.

The use of a multi-tracer gas, instead of a conventional single gas method, increases the speed and accuracy of interzonal air flow measurements⁶. It also clarifies specific flow directions. Gases which have been used include carbon dioxide, nitrous oxide, hydrogen, methane, ethane, helium, perfluorocarbons (PFTs) and sulphur hexafluoride. We have used perfluorocarbons and sulphur hexafluoride in our work as they have desirable tracer gas characteristics in terms of detectability, safety, and cost and they have been used successfully in air infiltration studies^{6,7,8,9}. Both SF₆ and PFTs exist only at very low background concentrations in the ambient and are easily detected (parts per billion range for SF₆ and parts per trillion range for PFTs) using an electron capture detector.

This paper is divided into two main sections. The first describes the development of the multi-tracer system for measurement of interzonal air flow in buildings. The second section describes a portable automated SF₆ system which has been used for measuring air change rates in a number of recently constructed tightly sealed houses in Milton Keynes, UK. The design, construction and calibration of the SF₆ system together with experimental results is also presented.

2. DEVELOPMENT OF A MULTI-TRACER GAS SYSTEM

Experimental work on interzonal air movement was previously carried out by Prior et. al.¹⁰ at PCL using an unrefined system consisting of automatic injection and sampling systems. During the present work this system has been improved with the development of the following:

2.1 Tracer Gas Injection

The rate of decay technique is used in our work as it requires relatively simple apparatus.

A number of injection units are being built. These simply consist of a 10 ml aluminium cylinder wrapped with a band heater and fitted with a sealing cap, Figure 1. Prior to each experiment, cylinders are injected with a known amount of perfluorocarbons and sealed in the laboratory. A programmable timer is used to energize the band heater during the test allowing tracer gases to be released simultaneously into a building. The following perfluorocarbons have been used in our work; perfluoro-n-hexane, perfluoro-methyl-cyclohexane, perfluoro-dimethyl-cyclohexane, and perfluoro-decalin.

2.2 The sampling System

The microcomputer-sampling system developed by Prior et al¹¹ may be improved with the following benefits: 1) greater speed of deployment within buildings, 2) a more compact and flexible system so it can be used during periods of a building occupancy, 3) reduced capital cost of the system.

The design of a compact and stand-alone sampling system is shown in Figure 2. The sampler consists of a 16-position, 34-port valve (type ST flowpath), made by Valco Instruments. The valve has an inlet port, an outlet port and a pair of ports at each of the 16 sampling positions. A six-position version of this valve and a sampling tube is shown in Figure 3. A small removable stainless steel tube, Figure 4, packed with a divinyl-benzene/styrene co-polymer adsorbent is connected to each pair of valve ports. Air at a constant flow rate may be drawn in each sampling point using a small pump and the multi-position valve is positioned by a stepping motor. A two channel digital timer is used as a control system to operate the stepping motor and pump. The operation procedure of the system is as follows. At the beginning of each experiment the valve is rotated to position 1 and the pump is turned on. At the end of the desired sampling collection time, set by the timer, the pump is turned off and the valve is rotated to position 2. This procedure is repeated

until all samples have been taken. The system is flexible since the sample loops may be filled in any desired sequence and at any desired time. The samples may be then stored for subsequent analysis in the laboratory.

Work has been completed on building one sampling unit and we are currently building further units of a similar design.

2.3 Tracer Gas Separation and Analysis

A new gas chromatograph, model 8410, made by Perkin Elmer is currently being commissioned. The chromatograph, which is fitted with an electron capture detector (ECD) and an ATD-50 thermal desorber, will be used for separation and analysis of the samples.

2.4 Measurements and Simulation Models

The new multi-tracer gas system will be used for measuring air movement in a number of recently constructed houses in the Milton Keynes area. Measurement will be carried out in other passive solar heated houses at Newham, UK. Some measurements may be carried out in Central Europe, providing suitable projects are located.

In the second phase of our programme, a comparison will be drawn between measurements of interzonal air flow and rates predicted using rules of thumb such as those developed by Balcomb et. al.¹² and using simulation models such as BREEZE and ESP¹³. In order to make comparisons with these models, work will begin on the implementation of the latest versions of the codes, at PCL, in the near future.

3. THE PORTABLE SF₆ SYSTEM

3.1 DESCRIPTION OF THE SF₆ SYSTEM

The SF₆ system used in this study consisted of the following:

3.1.1 The SF₆ Release System

The SF₆ release system consisted of a small SF₆ cylinder, a regulator and a solenoid valve. The solenoid valve is normally closed but is opened automatically using a BBC microcomputer. The volume of SF₆ gas released depends on the size of the building and is controlled by adjusting the length of time that the solenoid valve is open. The injection rate was determined by plotting the volume of gas released against time required for a constant pressure at the SF₆ cylinder outlet.

3.1.2 The SF₆ Measuring System

The microcomputer-measuring system is shown in Figure 5. The system was made up from the following major components:

- (a) Sampling and Injection Unit
- (b) Column
- (c) Chromatographic Oven
- (d) Electron Capture Detector
- (e) Microcomputer and Interface

The operation of the system is described, with reference to Figure 6. Argon, used as the carrier gas, normally flows at a constant rate through the column via the sampling valve. The carrier gas then passes through the detection cell before being vented to the atmosphere. The sampling unit consists of a two-position, 6-port valve, connected to a 0.5 cm³ sampling loop. The valve can be easily rotated to position 1 or 2 using a small motor.

The column was made by packing a 1.5 m x 4.3 mm i.d. nylon tube with 60-80 mesh aluminium oxide. The tube was coiled three times and placed horizontally inside an electrically heated oven. The oven was maintained at a constant temperature using a temperature controller. The electron capture detector, which uses Ni-63 radioactive cell, was made by Pye Unicom Ltd. This was also placed inside the oven as shown in Figure 5. A pump was used to draw air from the test space to create a flow through the sample loop. By rotating the sample valve to position 2, air in the sample loop was injected into the argon flow which carried it into the column and finally to the detector for analysis. The amplified reversed response from the detector cell is then displayed as peaks on the computer monitor as shown in Figure 6. The first peak represents the O₂ concentration in the sample and the second peak represents the SF₆ concentration. The system incorporates a BBC micro-computer with two 5¼ inch dual sided floppy disc drives, a parallel printer and interfaces for both analogue and digital data. The interfacing of the gas chromatograph and the sampling and injection units was accomplished by specially designed interface cards. The system is very flexible and can be used for unattended operation.

3.2 System Calibration

Calibration of the SF₆ system was carried out using the test rig shown in Figure 7. The rig consisted of 0.215 m³ capacity metal drum in which a small fan was used for mixing air and tracer gas. Air from a cylinder was line fed to an opening in the drum and its flow rate could be regulated between 10-150 and 100-1250 liters/hours using Brooks Ltd. Flowmeters. Provision was made

for the injection of SF₆ tracer gas into the drum and also for allowing the homogeneous SF₆/air mixture to leak out through a tube. Samples of SF₆/air mixture were drawn into tubes located at different levels in the drum. These samples were then passed through the ECD gas chromatograph for analysis. Experiments were conducted for infiltration rates in the range 0.1 to 2 air change/hour. The variation of measured air change rates using the SF₆ system versus calculated values using the flowmeters is presented in Figure 8. The coefficient of correlation was found to be 0.9947, the slope was 0.941 with an average error of 1.1%. The series of experiments showed that the portable SF₆ system gives reliable results.

3.3 TRACER GAS MIXING

The lack of good mixing of tracer gas with air could result in inaccurate measurement of the air change rate. Even so, a number of workers assume the concentration of tracer gas in a space is uniform and therefore measure the concentration at one point. Mixing problems may arise from buoyancy effects or from poor air circulation within the space due to internal partitions such as walls and furniture¹⁴.

To study buoyancy effects we carried out a number of tests in a closed container. A small amount of SF₆ was injected at the top of the container before it was sealed and left for about 45 minutes. The concentration of SF₆ was then measured at different heights. The concentration of SF₆ was found to be greater in the lower quarter of the container. Experiments were repeated with SF₆ injected at the lower part of the container with similar results being obtained. As a circulation fan was not used in our experiments it was suggested that the non-uniform concentration might be due to a slow mixing. To check this possibility the SF₆ was left in the container for a longer period and after about 2 hours the concentration of SF₆ was found to be uniform at various heights.

This experiment indicated that in tightly sealed houses an adequate period must be allowed for natural mixing and that buoyancy is not a problem with SF₆.

4. MEASUREMENT AND RESULTS

The tracer decay method has been used for measurement of air change rates in buildings. The decay method involves the release of a known volume of tracer gas into a building allowing sufficient time for the gas to mix with the air so that a uniform concentration is achieved. The dilution of the tracer gas is then monitored and is related to the air change rate according to:

$$C = C_0 e^{-At} \quad (1)$$

Where C is the measured tracer gas concentration at time t , C_0 is the concentration at $t=0$ and A is the air change rate.

Taking the natural logarithms of both sides of equation (1) we have:

$$\ln(C) = \ln(C_0) - A t \quad (2)$$

A plot of the best fit of $\ln(C)$ versus time is normally used to determine the air change rate. The volume flow of air, Q , in and out of the building is given by:

$$Q = A V \quad (3)$$

Where V is the interior volume of the building.

Air change rates were measured in a number of houses using the portable SF_6 system. The houses were built in Milton Keynes, UK, in 1985 and have been monitored since January 1986 by the Research in Building Group at the Polytechnic of Central London with funding from the Commission of the European Communities¹. Tests were carried out on these houses as follows:

4.1 Superinsulated Houses:

The superinsulated houses are three bedroomed, semi-detached units, each with a floor area of 75 m² and an attached garage. The houses were built to a superinsulated standard three times more than the stringent than the current UK building regulations. Vapour barriers were also installed for both the ceiling and walls of each house. A mechanical ventilation system with heat recovery is used to supply a controlled amount of fresh air and also reduce energy losses. This system was manufactured by BAHCO of Sweden, and uses an aluminium cross flow heat exchanger. The space and water heating are accomplished using a gas heating system.

During the test the ventilation system was used to introduce SF_6 into each house in order to achieve good distribution and mixing of the tracer gas. The amount of SF_6 released depended on the size of the building and also on the sensitivity of the detector. About 1 cm³ of SF_6 was released per m³ of space volume. Following an adequate mixing period, samples were taken every three minutes from several locations in the house to determine the degree of mixing and also to acquire an average concentration. With all windows and exterior doors closed measurements were taken on a house under the following conditions:

- a) Ventilation system switched off.
- b) Ventilation system operating in low mode.
- c) Ventilation system operating in normal mode.
- d) Ventilation system operating in boost mode.

The temperature difference between the inside and outside of each house and average wind speed during the measurement period were also recorded. The results of tests made in one of these houses are given in Table 1.

TABLE 1. AIR CHANGE RATE MEASUREMENTS IN SUPERINSULATED HOUSES

Time & Date	Condition	Air Change Rate (h^{-1})	Temperature Difference ($^{\circ}\text{C}$)	Wind Speed (m/s)
18.00, 16/4	a	0.10	15.5	1.3
10.00, 29/3	b	0.60	13.0	5.0
11.00, 28/3	c	0.90	13.5	6.7
13.30, 28/3	d	1.10	12.2	7.5

4.2 Control Houses

Control houses are almost identical to those that are super-insulated but differ in that they are not provided with a vapour barrier and their degree of insulation is only marginally above the current Building Regulation requirements. The control houses are heated with gas heating systems while ventilation is provided using slot ventilators in window frames. Air change rates were measured in these houses using the above method. Since these houses are not provided with mechanical ventilation systems, SF_6 was released at various points and fans were used to ensure that proper mixing was achieved. With all windows and exterior doors closed measurements were taken on a house under the following conditions:

- a) All vents closed
- b) Downstairs vents open.
- c) Downstairs and upstairs vents open.
- d) Slot ventilators removed and holes sealed with tape.

The decay of SF_6 under condition c) is shown in Figure 9. The results of measurements for three control houses are summarized in Table 2.

TABLE 2 AIR CHANGE RATE MEASUREMENTS IN CONTROL HOUSES

House No	Time & Date	Condi- tion	Air Change Rate (h^{-1})	Temperature Difference ($^{\circ}\text{C}$)	Wind Speed (m/s)
1	11.00, 24/2	a	0.23	15.0	2.5
	13.00, 24/2	b	0.52	14.0	4.0
	15.00, 24/2	c	0.87	14.1	3.0
	16.30, 24/2	d	0.31	14.0	3.2
2	11.00, 6/3	a	0.26	14.5	2.2
	14.00, 6/3	b	0.59	12.5	2.4
3	15.30, 6/3	a	0.20	16.0	4.5
	17.60, 6/3	c	0.94	17.5	4.3

The above results indicate the effectiveness of the slot ventilators in controlling the air change rates.

4.3 Courtyard Houses

The courtyard houses are a group of highly glazed passive solar houses, each is a four bedroomed, detached bungalow, with a floor area of 130 m^2 . Each house has a gas-fired heating system which uses a condensing boiler with zone control from thermostatic radiator valves. A BAHCO ventilation system with heat recovery was fitted in each of these houses.

House Number 1

Measurements of air change rates were carried out in this house with the ventilation system operating under the following conditions.

- a) Low mode
- b) Normal mode
- c) Boost mode
- d) High mode

The results are presented in Table 3, and the decay of SF_6 under condition b) is shown in figure 10.

House Number 2

This house is temporarily provided with a different type of

ventilation system with heat recovery in order to test its performance. The system, which is manufactured by Genvex of Sweden, supplies both ventilation and domestic hot water using a heat pump. The following operational modes were used:

- a) Ventilation system switched off
- b) Ventilation system switched off and fireplace sealed
- c) Ventilation system operating on normal mode
- d) Ventilation system operating on high mode

A summary of the air change analysis is given in Table 3.

TABLE 3 AIR CHANGE RATE MEASUREMENTS IN COURTYARD HOUSES

House No	Time & Date	Condi- tions	Air Change Rate (h^{-1})	Temperature Difference ($^{\circ}\text{C}$)	Wind Speed (m/s)
1	16.00, 19/5	a	0.51	6.0	3.8
	12.30, 19/5	b	0.68	1.7	2.5
	14.00, 19/5	c	0.81	3.7	2.7
	15.00, 19/5	d	0.84	4.8	4.0
2.	13.00, 18/5	a	0.23	6.7	4.0
	14.30, 18/5	b	0.16	6.3	4.2
	20.00, 18/5	c	0.42	9.0	4.0
	00.30, 18/5	d	0.54	9.5	3.5

5

CONCLUSIONS

(1) The use of the compact micro-computer SF₆ system has proved to be a reliable and a sensible approach for measuring air change rates in buildings.

(2) If SF₆ is allowed to mix naturally, then a period of about 2 hours is found to be essential if accurate measurements are to be made. Introducing SF₆ via the mechanical ventilation system of a building was found to be a good method for achieving quick distribution and complete mixing of the tracer gas.

(3) The measurement of the background air change rate for the superinsulated houses showed they are within the performance range standards of Scandinavian houses. Both tracer gas and blower door tests showed comparable results and confirmed the

airtightness of these houses. Ventilation rates under other operational modes were found to correlate well with figures calculated from duct air flow measurements.

(4) The use of slot ventilators and adequate heating in control houses was found to be a satisfactory means for reducing condensation. However, the efficacy of this approach critically depends on the way in which these ventilators are used by the building's occupants.

(5) Air change rates in the courtyard houses were found to be within the recommended ASHRAE standard and the mechanical ventilation systems were found effective in controlling the level of ventilation required.

ACKNOWLEDGEMENTS

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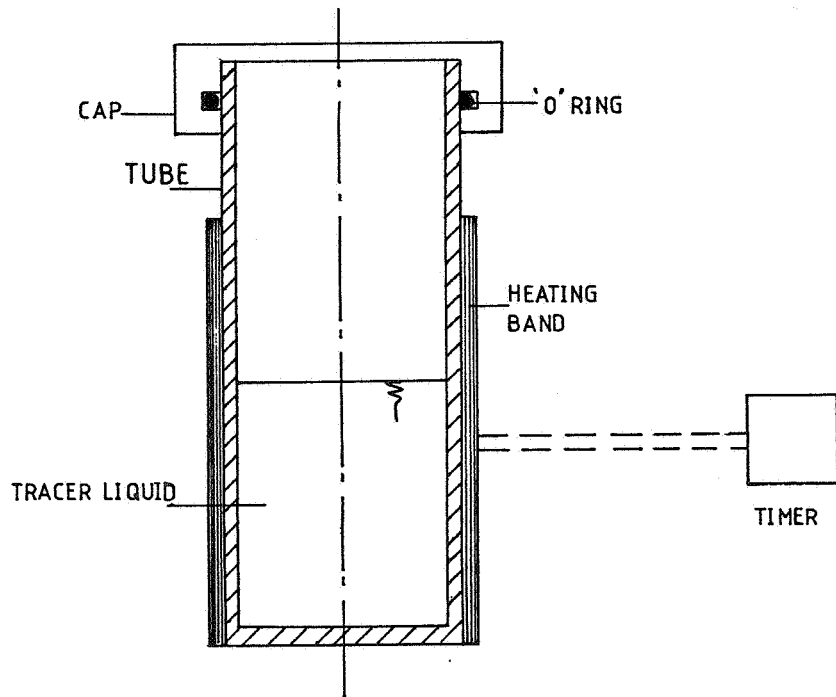


Figure 1
The tracer gas injection unit.

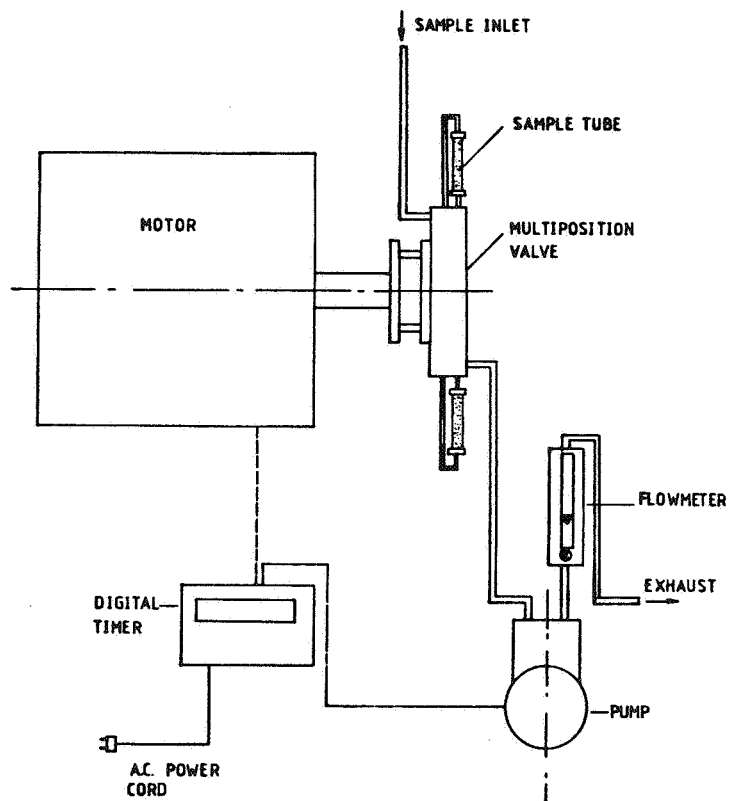


Figure 2
The multi-position valve sampling system

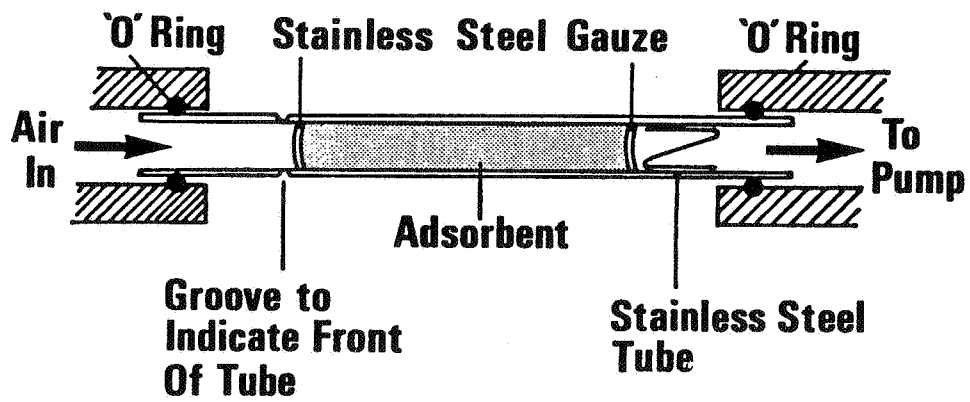


Figure 4
A single sampling tube.

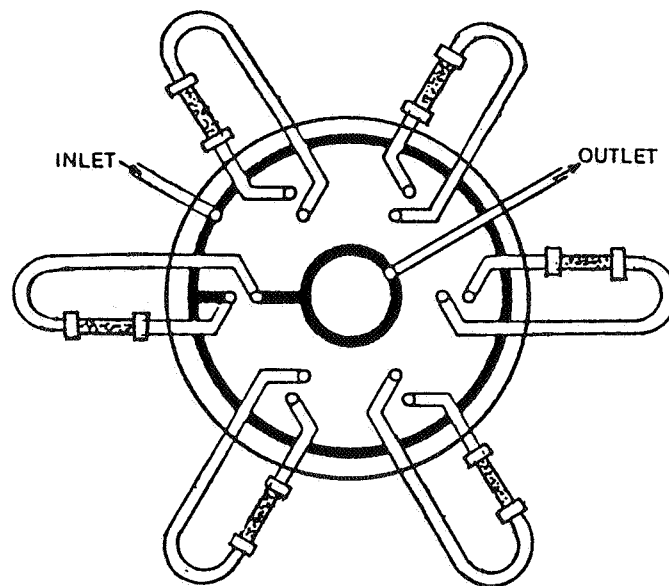


Figure 3
The six-position sampling valve

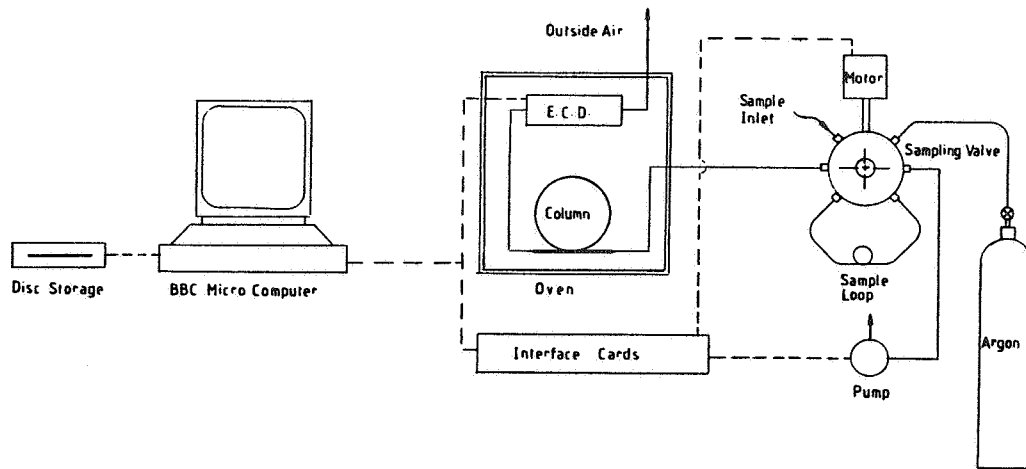


Figure 5.
The SF₆ System

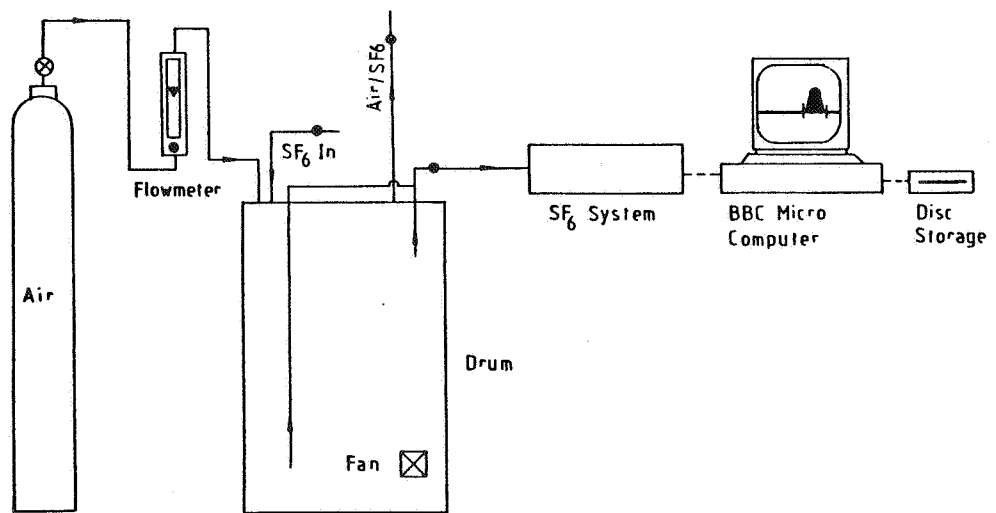
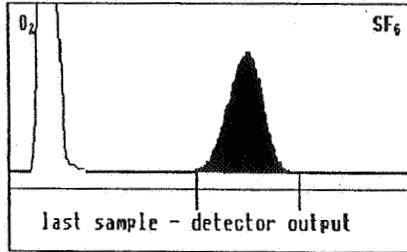
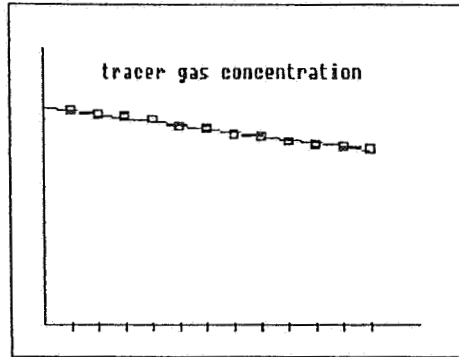


Figure 7
The SF₆ Calibration System

sample	time	conc	acr
1	15	31.3	
2	30	30.8	0.1
3	45	30.3	0.1
4	60	29.9	0.1
5	75	29.1	0.1
6	90	28.6	0.1
7	105	27.9	0.1
8	120	27.7	0.1
9	135	26.8	0.1
10	150	26.5	0.1
11	165	26.0	0.1
12	180	25.8	0.1



experiment data file - sinf5
 date of experiment - 16:Apr:06
 time of experiment - 18:00 hrs
 duration of experiment - 180.0 mins
 best estimate of acr - 0.1

Figure 6
The SF₆ system output

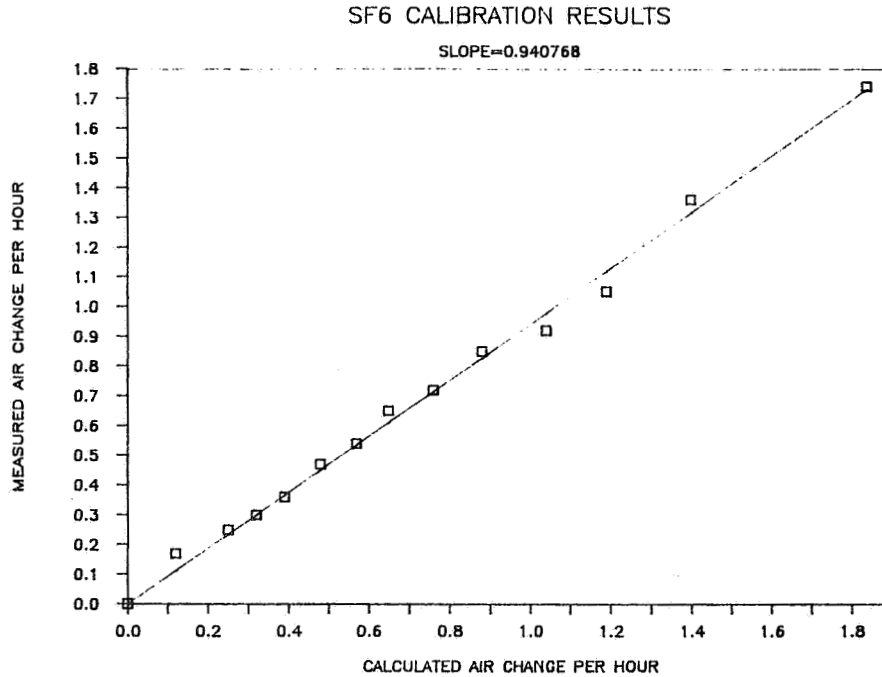


Figure 8
The variation of measured air change rates versus calculated air change rates.

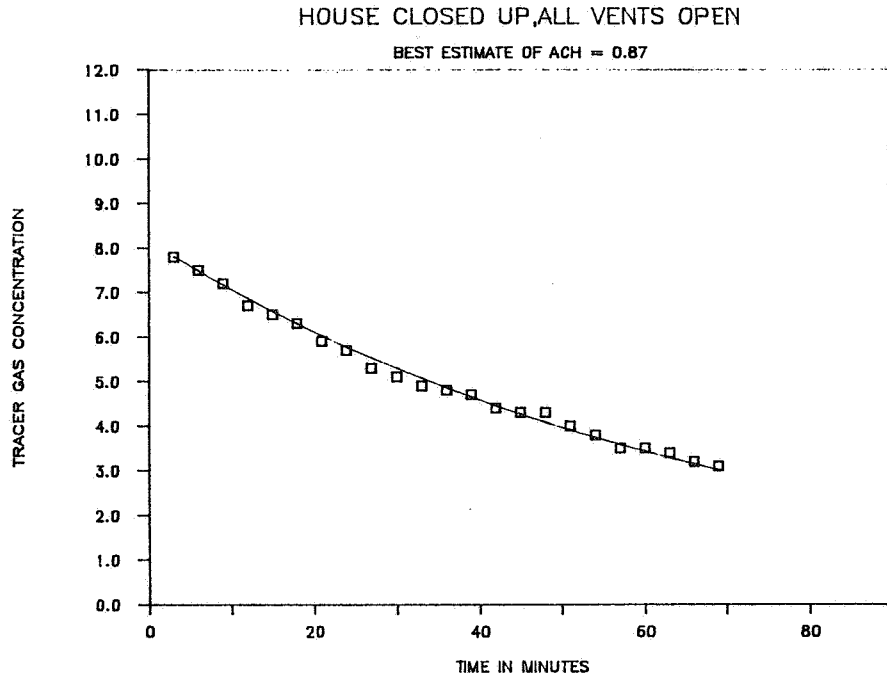


Figure 9
The decay of SF₆ tracer gas for a control house.

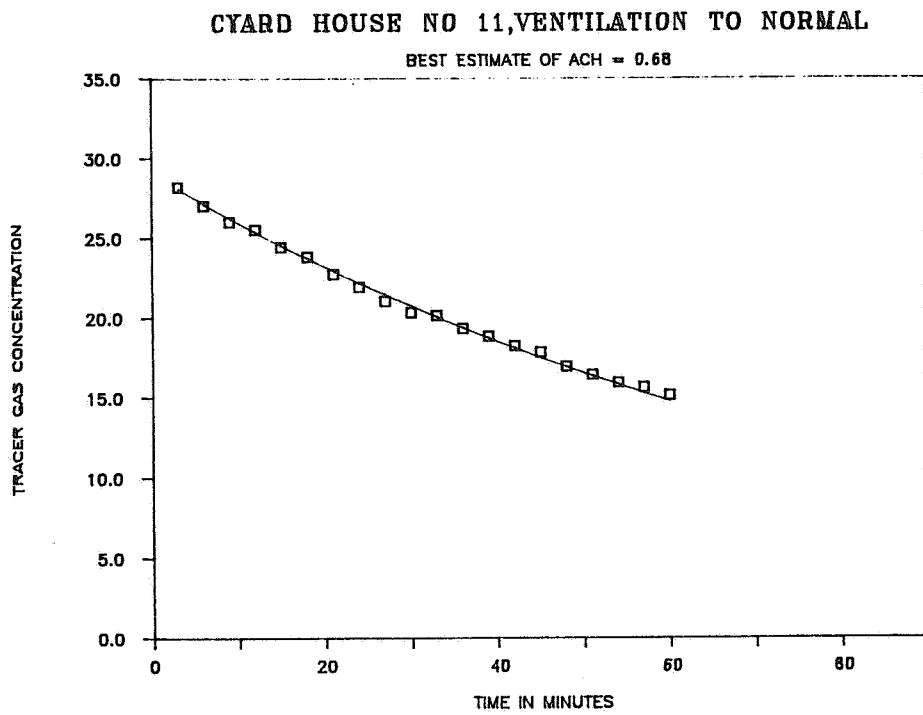


Figure 10
The decay of SF₆ tracer gas for the Courtyard house.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 4

TRACER GAS USED TO EVALUATE HVAC EQUIPMENT

BJØRN KVISGAARD
Brüel & Kjær
2850 Nærum, Denmark

P.F. COLLET
Technological Institute
2630 Tåstrup, Denmark

ABSTRACT

When controlling the performance of a ventilation system it is important to investigate how the system works together with the building it ventilates. It is the performance of the complete system which is of interest, not its individual components. This paper describes the use of a computer-controlled, tracer-gas measuring system for controlling ventilation systems.

By means of 4 measuring probes the condition of the air at the intake, room injection, room extraction and exhaust is registered. On the basis of these results, the computer can calculate the efficiency coefficients for the heat exchange, the percentage of air being recirculated, the outdoor short-circuit from exhaust to air intake and the percentage of extracted air resulting from room injection.

On the basis of field measurements with the equipment, the experience gained is discussed. In particular, it is interesting to see how large a percentage of the air blown through the ventilation system into the building is refound in the extracted air. Percentages of 60-80% are quite normal. If only, for instance, 60% of the injected air is returned, the building will have an air change which is at least 1.66 times the performance of the ventilation system.

INTRODUCTION

Badly planned, badly made, badly regulated and badly maintained ventilation systems are some of the most frequently reported causes of problems with the indoor climate in office buildings and dwellings. Lacking or incorrect maintenance of ventilation systems is probably the biggest problem of them all. Having a service contract with a ventilation firm and an automatics firm may be useful, but it does not ensure that the ventilation system will work as it should do. The measurements we made in buildings where the ventilation systems were systematically maintained, revealed such serious faults that it is questionable whether the type of systematic maintenance carried out today is worth the expense.

There are many answers as to why so many ventilation systems work badly. One of them is simply that it is difficult for the people working in the building to discover the faults. Another is that the requirements laid down for checking ventilation systems are very limited. A third is that the people who look after the ventilations systems are inadequately trained.

A way in which to improve the maintenance standard for ventilation systems is to perform frequent measurements on them. It is the performance of the complete system which is of interest, not its individual components. What is needed therefore is to check how the ventilation system works together with the building it serves instead of controlling the individual components in the system. Such a performance check of the ventilation system does not distinguish between the individual types of faults, as it concentrates on the product which the system supplies. The results of such a performance control can be:

- air changes for the building
- ventilation efficiency
- contamination in the injected air
- contamination in the extracted air
- temperature levels in the building
- energy consumption for ventilation

In this article we will describe computer-controlled measuring equipment which can measure most of the above parameters automatically.

MEASURING METHOD

For the measurement of ventilation systems we have used one of the continuous air change measuring instruments from the Technological Institute. The only thing that has been changed is the software, i.e. instead of the normal program which controls the measurement with "constant concentration of tracer gas", a newly developed program has been installed which is specially designed for ventilation systems.

The measurement is made where the ventilation unit is placed, but is not made in the actual unit, only in the inlet and outlet ducts. By using 4 probes, the condition of the air in the ducts can be measured for outdoor air intake, room injection, room extraction and exhaust. As all the measurements are made close to the ventilation unit, the equipment can be set up very quickly and the time-consuming hanging up of tubes and wires is avoided. The position of the measurement points can be seen on figure 1.

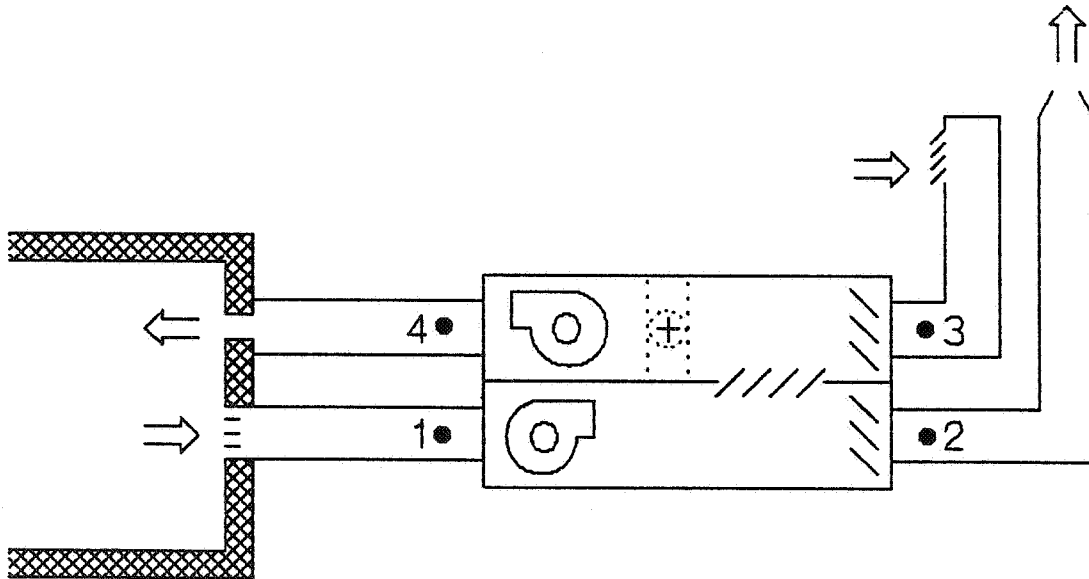


Fig. 1 Diagram of the ventilation system with the position of measurement points.

The parameters measured are:

- quantity of injected air
- quantity of extracted air
- quantity of air recirculated through mixing dampers
- outdoor short-circuit from exhaust to air intake
- percentage of injected air in the extracted air
- temperature in all 4 ducts
- air humidity in all 4 ducts
- content of CO_2 in injection and extraction
- any other interesting contamination components.

Tracer gas is used for the measurement of air quantities, recirculation percentages, outdoor short-circuit from exhaust to air intakes and percentage of injected air present in the extracted air. IR analyzers are used for the measurement of tracer gas concentrations, contamination and humidity content.

On the basis of the parameters measured, the efficiency of heat recovery, if any, can be calculated, and it is furthermore possible to calculate a minimum value for air infiltration in the building.

Each measurement probe has several functions as it can dose tracer gas, collect air samples and measure the air temperature. Due to the short distance between dosing and collection point, air samples cannot be taken at the same time as the tracer gas is being dosed at a point. The measurement of the individual flow and recirculation percentages must therefore be made in series. A measuring cycle can, for instance, be divided into the following 5 steps:

1. Measure the quantity of injected air by first measuring the concentration of tracer gas at point 4, then dose tracer gas at point 3 and measure the increase in the concentration at point 4.
2. Measure the quantity of extracted air by first measuring the concentration of tracer gas at point 1, then dose tracer gas at point 2 and measure the increase in the contraction at point 3.
3. Measure the recirculation in the mixing dampers, by dosing tracer gas at point 1 and measuring the concentration of tracer gas in points 2, 3 and 4. The concentration at point 4 will be a result of the mixture of extracted air and outdoor air.
4. Measure outdoor short-circuit by dosing tracer gas at point 2 and measure the concentration at point 3.
5. Measure the percentage of injected air present in the extraction by measuring the concentration of tracer gas at point 1. On the basis of the known quantity of injected air, recirculation in mixing dampers and dosed tracer gas quantity, the mean concentration of tracer gas in the injection can be calculated. If the concentration of tracer gas measured in the extraction from the room is divided by the calculated mean concentration in the injection, the percentage of injected air present in the extraction is obtained.

In order to keep the error margin to a minimum when determining step 5, the dosing of tracer gas at point 3 must be controlled so that the injected air always contains a constant concentration of tracer gas as a mean over a cycle.

MEASURING RESULTS

The measurements were made in a 13-floor high-rise building.

The building had 96 dwellings each with 2 or 3 rooms. The measurements were carried out in the northern half of the building, serviced by a ventilation system placed on the roof of the building. The ventilation system injected air into the living rooms and other rooms of the dwellings and extracted air from the kitchens and bathrooms. The plant was equipped with a heat-recovering system transferring energy from the extracted air to the injected air. All channels from the ventilation system down to the flats were on the outside of the building.

When the measurements were being performed, the wind velocity was approx. 2 m/sec. and the outdoor temperature approx. -3°C . The measurements were carried out while the dwellings were occupied and the occupants could thus open both windows and interior doors.

The mean values for the volume flow measurements can be seen in figure 2.

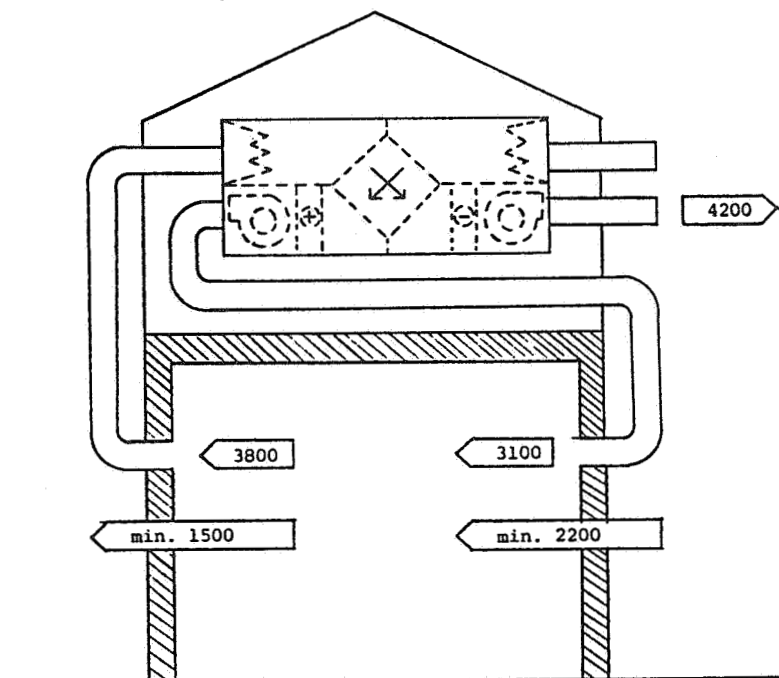


Fig. 2 Measured and calculated quantities of air in m^3/h of the 48 dwellings in the building.

The air change taking place in the dwelling which is not caused by the ventilation system, is calculated on the basis of injected and extracted volume flows as well as the percentage of injected air present in the extraction. For calculation purposes, the assumption is made that all rooms in the building have the same concentration of tracer gas as the one measured

in the extraction. This assumption means that the air change resulting from airing out the rooms is underestimated. In fig. 2 the quantities of air are therefore stated as minimum quantities of air.

Main data for the measurement were:

Injected volume flow	full performance	5000 m ³ /h
	half performance	2000 m ³ /h
Extracted quantity of air	full performance	5700 m ³ /h
	half performance	2600 m ³ /h
Recirculation in ventilation unit		not measurable
Outdoor short-circuit		not measurable
Percentage of injected air in extracted air		59%
Mean air change for dwellings		5300 m ³ /h 0,61 ACH
Humidity injection		3.22 g/kg dry air
extraction		4.95 g/kg dry air
Amount of energy supplied for injection air in ventilation unit		26,7 kW
Amount of energy recovered from exhaust air in ventilation unit		17,0 kW

A discovery of the measurement was that the extraction fan receives approx. 10% of its air from the control room or from the outdoor air duct in the ventilation unit. Another by-product of the measurement was that the unit was changed, because the heat recovery was not as efficient as expected.

CONCLUSION

Tracer gas measuring equipment has proved to be very efficient with regard to trouble-shooting in ventilation systems, and it is also an efficient tool as a basis for the evaluation of the indoor climate. In addition to providing information about injected and extracted quantities of air it also gives the minimum value for air infiltration in the ventilated rooms. When evaluating the indoor climate in a building it is very useful to know how large a percentage of the air change is due to the ventilation system and how large a part to leaks in the climatic shield and the rooms being aired out. In the building measured the

ratio was approx. 60% to the ventilation system and approx. 40% to leaks and rooms being aired out.

The measuring equipment makes it possible to evaluate the quality of the injected air as regards the contamination, humidity content and temperature. The load on the building can also be assessed by looking at CO, CO₂, humidity content and temperature in the extracted air.

One of the disadvantages of the equipment in its present form is that it measures on the whole ventilation system, and therefore does not give much information about how well the flow is adjusted for each room.

The question of whether this type of measuring equipment is the best suited for performance control is difficult to answer. Today we only have limited experience with how much time a measurement takes and how expensive it is to perform a measurement.

The principle of carrying out performance control of ventilation systems is a very efficient control. It should therefore be made on all new systems before they are delivered. For larger systems, function control should also be made at frequent intervals as a monitoring of the operation of the system.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 5

APPLIANCE OF INFRARED-THERMOGRAPHY IN EXAMINING AIRLEAKAGE OF BUILDINGS

ir. O.C.G. Adan
ir. L.W.J.L. Hendriks

Rijksgebouwendienst (Government Buildings Department)
Afdeling bouwfysica (Building Physics Section)
P.O. Box 20952
2500 EZ 's Gravenhage
The Netherlands

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The research regarding the application of thermography was financially supported by the Management Office for Energy Research (PEO)

The thermographical analysis has been carried out by EARS bv (Ingenieursbureau voor 'Environmental Analysis and Remote Sensing'.

PREFACE

Ventilation of buildings proceeds from actual ventilation due to applied ventilation-facilities in conformity with the standards and regulations, and from unaware ventilation due to cracks and seams in the building envelope. This uncontrolled air-exchange can substantially influence the total ventilation and can therefore result in problems.

The capacity of heating-installations have become considerably small as a result of increased thermal insulation of buildings. Due to this it is quite possible that the installation can no longer provide the required indoor-climate at a too large undesirable infiltration of outdoor-air under extreme outdoor-climate conditions. There is hardly any capacity left to deal with these unexpected interferences. Besides, excessive outdoor-air infiltration leads to extra energy consumption because the air in winters must be heated, and, in complete air-conditioned buildings, air in summers must be cooled. This excessive infiltration can interfere with the aimed ventilation of rooms via ventilators, flap-windows and mechanical systems. There is also a higher risk for damages by condensation at concentrated leakages.

The previous motivates the setting of a (maximum) limit to the airtightness requirements in The Netherlands. Since 1982, the Rijksgebouwendienst have made demands into practice on the minimal airtightness of building façades. These demands were formulated according to the NEN 3660 and NEN 3661: "window frames - air permeability, rigidity and strength - methods of test, requirements". These standards contain product-requirements for the texture elements of the buildings envelope, such as lower fronts of buildings, windows and doors, and therefore have no (direct) regard to the in the practice occurring airtightness of the building envelope as a whole.

The joints between the several texture building elements play an important role for the airtightness of the complete envelope. However, the demands in these standards are being reconsidered at the moment.

Based on guide-lines formulated by the Rijksgebouwendienst, a standard is being prepared in which demands on airtightness of the complete building envelope in the practice will be formulated. This implies that an evaluation measuringprocedure is to be prescribed. The application-field of these new norms concerns primarily the utilitarian buildings, such as office buildings.

Meanwhile, two draft standards for dwellings (or all buildings intended for occupation) have been prepared. (NEN 2686 and NEN 2687 concerning measuringprocedure, respectively requirements) The demand for dwellings (or buildings intended for occupation) merely involves a net airvolume- current at a distinct pressure difference between the building and outside. On account of this, a rough indication of the construction quality is given in relation to the chosen ventilation system. Interpretation of the ventilation system to the energy consumption requires knowledge of several aspects such as distribution of airtightness over the envelope, the ventilation system and the distribution of temperature in the building.

The standards with regard to the utilitarian buildings as well as the standards for buildings intended for occupation, merely state a minimal required quality: in which manner this should be realized is not stated. Naturally, the airtightness will for a large part depend on the attention, which has already been paid in the design proces to an airtight detailing.

After this the guide-lines for façades operated by the Rijksgebouwendienst (The Government Buildings Department) as well as the measuring-procedure as an evaluation of those in the practice will be dealt with. Fifty airtightness-measureings in thirty government buildings have been carried out in the period 1980 up to 1985. The measurements have been evaluated.

The measuring-procedure operated so far by the Rijksgebouwendienst is an evaluation of the quality of the façade by means of a random test: a representative considered fragment of the façade, mostly a repeating part is tested. This procedure should be carried out in an as early as possible stage, so that systematical errors can be determined.

Beside this, evaluations in problemsituations can be carried out afterwards. The use of infra-red thermography as an aid has been researched to achieve a qualitative and if possible, quantitative indication of airtightness(distribution) of the complete building envelope. The results of this thermographical research, which is combined with architectural research on the spot, are dealt with in paragraph 7, 8 and 9.

1

GUIDE-LINES OF THE RIJKSGEBOUWENDIENST

The Rijksgebouwendienst have, so far, set demands on airtightness of façades as a whole as well as average airtightness of cracks and seams separately. The requirements formulated for airtightness of façades as a whole are decisive. The requirements on cracks and seams (this is the space between construction parts which are meant to be able to move in respect to one another) differs from the product demand in the NEN 3661 in that it may not conflict with the demand on the façade as a whole. This means that buildings with a large crack length per m² façade have an increased requirement on the airtightness of the cracks/seams. (limit-value of 0,6 m¹ seam per m² outdoor-surface).

The requirement on the façade was set at that time according to the standards NEN 3660 and NEN 3661. This implies that the following is considered acceptable: 'the situation, in which during one hour a year at the most, an amount of outdoor air gets in through cracks and seams which is equal to or larger than the desired amount of air necessary for ventilation'.

In the derivation of the requirements on façades as a whole, we started from a standard office, in which in case of a single room there is question of an average outdoor-surface of 8,4 m² and in case of rooms for more than one person, the outdoor-surface varies from 4,0 to 4,7 m². At a minimum amount of ventilation of 9,7 l/s a person (= 3,5 m³/h a person) in terms of fragrance hinder, a minimum ventilation necessary is found varying from 1,2 to 2,4 l/s.m².

According to the starting-point of the NEN 3661, these amounts serve as a model for the admissible infiltration (amount) at a distinct pressuredifference over the façade, the so-called evaluation-pressure. At the starting-point of exceeding a maximum of one hour, the evaluation-pressure is co-determined from wind-velocities, which at certain heights at a maximum of one hour a year are exceeded.

An admissible airtightness of the façade of 1,8 l/(s.m²) at evaluation-pressure has been determined to set a uniform demand on grounds of economical considerations. This requirements applies to façades with parts that can be opened. A slight airleakage for completely sealed façades is believed in practice to be reasonably attainable so that a more aggravating demand can be used: 0,5 l/(s.m²) has been chosen as a first, naturally arbitrary, criterium.

A distinction in demands for façades with openable elements and entirely sealed façades is not relevant on grounds of the chosen starting-point: the same admissible volumecurrent applies for both. Aggravating the demand for sealed façades cannot be motivated on grounds of economical considerations. Buildings with completely sealed façades, however, will mostly be entirely (air)-conditioned, so that aim at slighter airleakage is advisable in terms of interference of the installation. Concerning the preparation of a Dutch standard, this subdivision is still up for discussion with regard to the airtightness of the entire building envelope.

The guide-lines of the 'Rijksgebouwendienst' will link up to this new standard.

The present-day guide-lines of the 'Rijksgebouwendienst' have been evaluated to find out to what extent these can be realized in the practice. This was done on grounds of an evaluation of 50 airtightness measurements in the practice carried out by the 'Rijksgebouwendienst' in the period of 1980 up to 1985. The conclusions which were drawn are dealt with in paragraph 3.

2 MEASURINGPROCEDURE AIRTIGHTNESS OF FAÇADES

The procedure used by the 'Rijksgebouwendienst' for determining the airtightness of a representative esteemed façadefragment, is in principle as follows: an airtight pressurechamber is placed on the inner-side of the construction up for testing. The sealed experimental room is brought to a certain over- or underpressure by means of a ventilator. The pressure difference of the experimental room and the outdoor-climate as well as the air quantities supplied and drained are registered. The net amount of m^3 air is determined by measuring the pressure difference over a measuring-flance assembled in the air supply hose. The Afdeling Bouwfysica of the Rijksgebouwendienst use two slanting tube manometers (pressure-gauges). In preparation of the measuring, the airtightness of the room's walls are checked and a short pre-pressurization is carried out according to the testprocedure for façade-elements in the NEN 3660. Pressure is built up gradually when determining the airtightness of the façade-element. The testing takes place at overpressure as well as underpressure. If the measurements show that the façade does not meet the demands, another closer investigation for air-leakages in the façadeconstruction takes place. The measuringprocedure is repeated after sealing the (possible) leakage. The average airtightness of cracks/seams is also determined in that manner. The measuring is mostly concluded by the conducting of a smoke-experiment. The most important airleakages can be localised by placing a smoke source and the airtightness of the pressure chamber can be evaluated in comparison with the tested façadefragment. A quantitative evaluation on grounds of withdrawing smoke quantities is naturally not possible.

3 EVALUATION OF MEASURING AIRTIGHTNESS IN PRACTICE

Table 1 shows an overall picture on airtightness measurements with façades in the practice, conducted by the Afdeling Bouwfysica of the Rijksgebouwendienst in the period of 1980 up to 1985. On ground of these results, the following conclusions are drawn:

The current guide-line of $1,8 \text{ l/(s.m}^2\text{)}$ for façades with openable elements at a well-considered specification of the sealing of cracks/seams and a careful execution in the practice as well is stated to be easy to realize if airlosses through leaks in the testroom walls to other rooms in the buildings are taken into account. Almost all investigated projects during the execution-stage appeared to be able to meet the requirements, although this was realised after dealing with the matter. The extreme benefit of airtightness measurements in an early stage of the construction is therefore emphasized; problems occurring later can be solved at an early hour.

In general it is concluded that in case the façade does not meet the requirement, the cause must mostly be searched in a insufficient sealing of the cracks/seams, where the joints of the façade-elements and the surrounding buildingconstructions are. Especially the joint of the window-frame and the surrounding masonry and in particular the joint of the bottom rail on the parapet is a regular noted leak. It has also appeared that seams cause problems more often than cracks.

From the measurements, it appears that the airtightness of cracks at evaluation pressure vary from $0,04 \text{ l/(s.m}^1\text{)}$ to $2,46 \text{ l/(s.m}^1\text{)}$ with an average of $0,95 \text{ l/(s.m}^1\text{)}$ (excepting the 'Belastinggebouw' in Haarlem and the 'Gerechtelijk laboratorium' in Rijswijk: here no sealing was applied).

It is also stated that the current requirement can simply be met although the airtightness of cracks has been determined separately in a limited number of measurements. It has appeared from experience that most critical constructions, concerning crack-sealing, mostly sash-window, can meet this requirement. Besides this, it is stated that a requirement for cracks of $2,5 \text{ l/(s.m}^1\text{)}$ in the draft version of the NEN 3661 (august 1986) will be copied. Therefore the current guide-line of the 'Rijksgebouwendienst' can be maintained or a reference to the new version of the NEN 3661 can in due time be enough.

An airleakage of maximum $0,5 \text{ l/(s.m}^2\text{)}$ in the practice is in fact realizable for buildings with entirely sealed façades. This is concluded from the measurements, taking into account the aircurrent from the testroom to other rooms in the building. Same as with the façades with openable elements, it has appeared that insufficient sealing of the seams mostly leads to dramatical consequences for the airtightness of the façades as a whole.

With regard to the requirements to the airtightness of seams in the practice, it is concluded that an (average) quality requirement per m^1 seam is not manageable, since the in the practice occurring problems when determining the active seamlength and the interpretation of the definition : seam.

Besides, it is not relevant to set a requirement to the average airtightness of all other leaks, mostly seams, since the requirement to the airtightness of the façade is representative and that also a separate requirement to cracks is set. It is recommended to prevent concentrated airleakages in terms of human comfort and risc for local condensation.

	l_c	$P_{eva.}$	Q_f	C_f	Q_c
Rijksinkoopbureau Zwolle	0,53	150	2,2	76	-
Belastingkantoor, Assen	0,46	150	1,8	62	-
(after sealing)			0,6	22	-
Rijkspolitie, Waddinxveen	0,35	150	0,7	24	-
CBS, Heerlen	1,08	200	1,0	29	0,48
Min. O&W, Zoetermeer	0,65	200	3,9	115	-
(after sealing)			1,5	44	-
(after sealing)			0,5	15	-
Belastinggebouw Haarlem	0,64	200	8,4	247	7,39
Min. O&W, Zoetermeer	0,70	200	0,6	18	-
Rijkskantorengedouw, Lelystad	0,85	200	4,1	119	-
(after sealing)			1,2	36	-
Min. Bu.Za., Den Haag	0,23	200	4,1	120	-
(after sealing)			1,1	33	-
R.S.G., Steenwijk	1,22	150	2,6	91	0,11
Topografische Dienst, Emmen	0,99	200	3,5	101	-
(after sealing)			1,3	38	-
Belastinggebouw, Haarlem	0,33	200	2,6	75	-
Belastinggebouw, Hoorn	-	200	2,6	75	-
Gerechdelijk Lab. Rijswijk	0,70	200	8,8	259	5,38
(after sealing)			2,2	64	-
C.B.S., Haarlem	-	200	4,4	-	-
Rijkskantorengedouw Eindhoven	0,78	200	2,2	64	0,04
G.A.B., Lisse	0,50	150	20,9	740	-
(after sealing)			4,0	142	-
Gerechdelijkgebouw, Breda	0,98	150	4,1	144	0,25
(after sealing)			2,0	70	1,16
Nieuwbouw P.T.T., Krommenie	0,23	150	1,0	37	1,70
Rijkspolitie, Den Bosch	0,22	150	2,5	90	-
R.P.A., Alkmaar	1,14	150	5,1	180	1,10
R.S.G., Epe	0,69	159	4,1	144	2,46
R.S.G., Enkhuizen	0,30	150	30,6	1085	-
(after sealing)			8,2	292	-
Rijks Inkoop Bureau, Zwolle	0,33	200	3,7	107	-
R.S.G., Harderwijk	0,31	150	2,4	85	1,33

Table 1 Measurements of buildings with openable elements.

Symbols:

l_c mean crack length per m^2 façade (m^1/m^2)

$P_{eva.}$ evaluation-pressure (Pa)

Q_f net air volume current per m^2 façade at evaluation-pressure ($l/(s.m^2)$)

C_f "C-coefficient", air-leakage per m^2 façade per Pa pressure difference ($l/(s.m^2.Pa^{2/3})$)

Q_c net air volume current per m^1 cracklength at evaluation-pressure ($l/(s.m^1)$)

	$P_{eva.}$	Q_f	C_f
Koninklijke Bibliotheek, Den Haag	200	1,0	30
Centraal Belastingkantoor, Utrecht	250	1,4	36
Min. Bi.Za., Den Haag	250	3,4	86
Nieuwbouw Ac. Ziekenhuis, Leiden	250	0,5	12
Rijkswaterstaat, Den Haag	250	2,8	70
(after sealing)		0,7	18
R.I.V.M., Bilthoven	200	6,9	202
(after sealing)		2,3	67
W.V.C.-A, Leidschendam	200	10,1	296
(after sealing)		7,9	230
W.V.C.-M, Rijswijk	200	19,5	570
(after sealing)		17,7	517

Table 2 Measurements of façades without openable elements.

Symbols:

$P_{eva.}$ evaluation-pressure (Pa)

Q_f net airvolumecurrent per m^2 façade at evaluation-pressure ($l/(s.m^2)$)

C_f "C-coefficient" ,air-leakage per m^2 façade per Pa pressure difference ($l/(s.m^2.Pa^{2/3})$)



Fig. 1 Airtightness measuring in practice; equipment of the Rijksgebouwendienst.

INFRA-RED THERMOGRAPHY

Infra-red thermography, in short: thermography, is based on detection of longwave radiation sent out by solid bodies. A difference is made between absolute and differential thermography. Surface temperatures can be read directly by means of absolute thermography, differential thermography visualizes temperature-differences on surfaces. As a result of difficult controllable measuring circumstances, application of thermography in analysing building constructions mostly refers to differential thermography. Infra-red thermography must also not be confused with infra-red photography. Radiation can be visualized as well by means of infra-red photography, however the wave-lengths for which photographic material is sensitive, are much shorter. This implies that infra-red photography can only be used if solid bodies have a relative high temperature (of more than 250 °C), or if radiation from a radiator with a high temperature (for instance the sun 5000 K) is reflected. We shall not go further into the matter of infra-red thermography technics (recording, videoamplifying, display).

Figures 2 and 3 show the recording of a construction part with visible light and infra-red thermography respectively. The local white discolorations in the thermographical recording are higher surface temperatures.

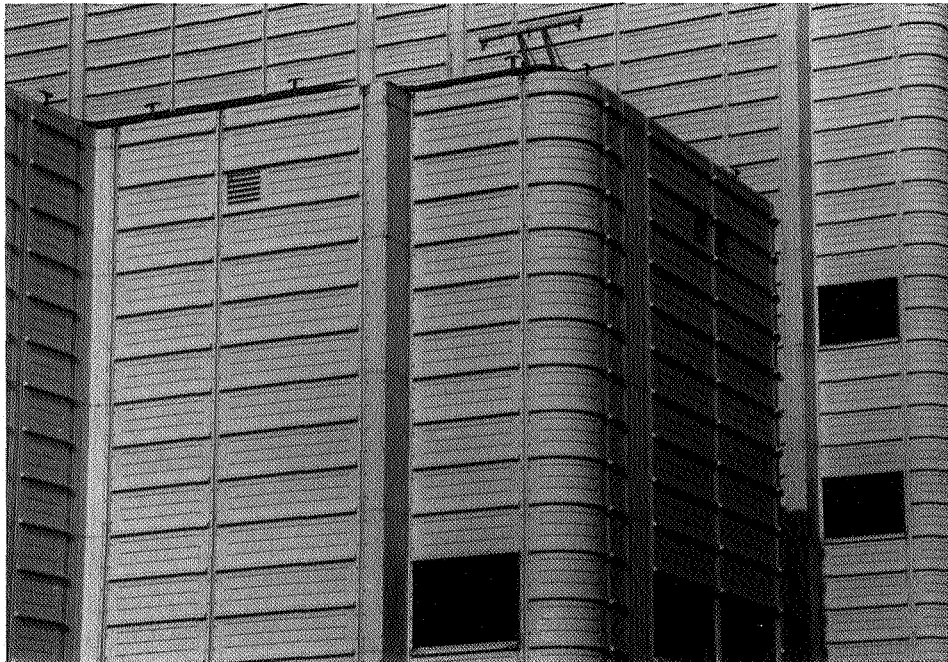


Fig. 2 Visible light recording of af construction part.

THERMOGRAPHICAL RESEARCH IN AIRTIGHTNESS

Introduction

In the beginning the application of thermography was primarily focussed on examining retrofit-projects. Inspections were carried out during retrofit or afterwards by means of thermography. Two types of temperature differences were regularly noticed when carrying out the thermography and its pre-discribed objective:

- differences regarding the conduction of the construction (thermal bridges)
- differences as a result of airleakage

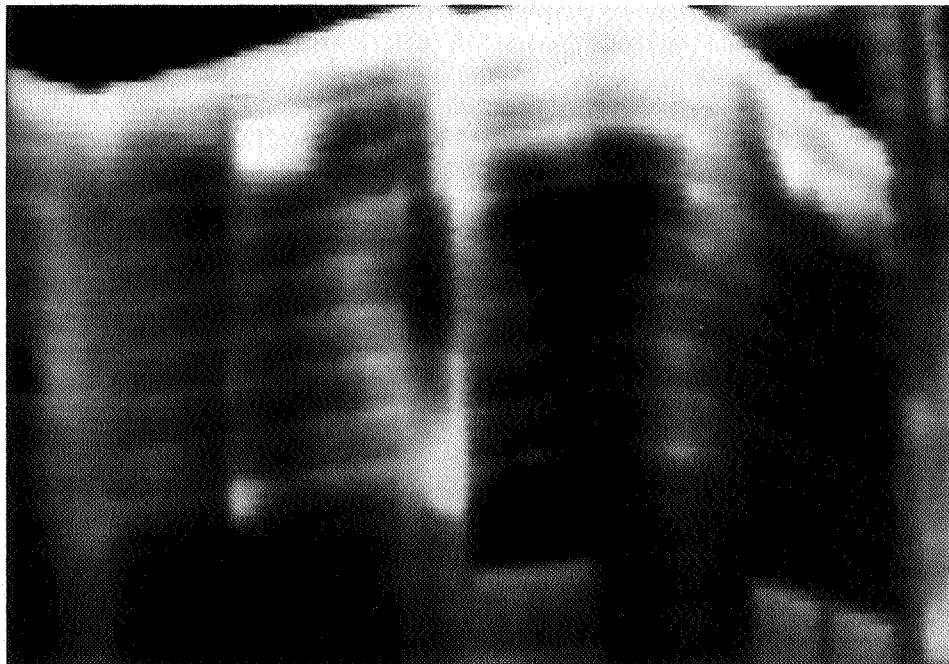


Fig. 3 The same building part shown in figure 2 as a thermographical recording. The local white discolorations in this recording are higher surface temperatures.

Thermographical analysis of a number of buildings with problems with regard to airtightness showed, if the building is brought to a slight overpressure, infra-red thermography could possibly be used for detecting airleakages. From this a pre-investigation started to the applicability of infra-red thermography for detecting airleakages.

5.2 Research objective

The research has two objectives:

- Utility of infra-red thermography for detecting airleakages.
 - . evaluation of the ability to detect differences in airtightness.
 - . evaluation of the ability to distinguish differences in airtightness from all other causes of temperature differences by means of this method.
 - . formulation of the conditions in which the method can be successfully applied.
 - . research in possibilities to quantify airloss on grounds of thermographical recordings.

- Architectural evaluation of the detected deficiencies
 - . systemize the detected deficiencies according to cause and location in the construction of the building.
 - . On grounds of this, development of architectural recommendations to prevent problems with airtightness.

5.2 Research procedure

The research consists of 3 parts:

- Thermographical research of 11 (eleven) officebuildings,
- Architectural research of the reported temperature differences,
- Airtightness tests accordingly to the procedure described in 2, combined with thermography, of a façadefragment at three of the researched buildings.

The thermographical research in the eleven buildings was aimed at locations on the building surface which seemed to be airleakages. In the architectural research is determined whether there is a question of airleakage at the distinct locations. Furthermore is determined how leakages occur and if no airleakage is the cause of the temperature difference: What is ? The thermographical recordings contain quantitative information on temperature differences on the facade. Researched is whether it is possible to calculate the leaking volume current from this information. Therefore airtightness tests have been carried out together with thermographical analysis. The results of airtightness tests contain the absolute airlosses through a façade element at a distinct pressure difference between indoor and outdoor. The thermography, which is carried out at the same time, supplies information on the involved temperature differences. The connection between both is examined.

6 THE RESEARCH

6.1 Building selection

Eleven buildings were selected from all governments buildings for this investigations. All buildings were thermographically researched. From the buildings researched in this manner, 3 buildings were selected. Here an airtightness test was carried out together with thermography.

6.2 Thermographical research

The thermographical research was focussed on detecting different temperature-differences on each building surface. It was therefore not necessary to investigate the entire building. Only a few smaller buildings were almost completely investigated at the outside. In most buildings also an investigation was carried out at selected locations on the inside. The thermographical recordings were recorded on video-tape during the investigation and then worked out in a report which contained selected thermogrammes for architectural research.

Only those recordings were worked out where the temperature differences were interpreted as airleakages. The distinguish between temperature differences as a result of airleakage and other temperature differences was made on grounds of the type of difference in the thermogramme and the location on the construction.

6.2.1 Circumstances during thermographical analysis

Before carrying out the thermographical research, several requirements were set with regard to measuring period, difference between outdoor- and indoor temperature and wind-velocity in connection with pressure difference over the façade.

- The measuring period.
The measuring period is in the second half of the night, so that temperature

differences on the façade surface as a result of difference in radiation during the previous day can be avoided as much as possible. The analysis was stopped before or around sunrise.

- Temperature difference between indoor and outdoor.

Because a difference between airtemperature indoor and outdoor must be available, a requirement of minimum 10 K has been set. This has never been a problem during the investigation. The difference has always been amply realized by increasing the temperature in the building.

- Pressure difference over the façade and windvelocity.

Windvelocity influences the pressure difference over the façades. At higher windvelocities, the weather-side has an overpressure and the lee-side an underpressure. Therefore the thermographical visualization will differ from façade to façade. Also temperature patterns if any, become blurred at high windvelocities.

Many buildings have a mechanical ventilation system which makes it possible to create an overpressure in the building. By creating an overpressure in the building the influence of airvelocity is deminished. First the choice fell to measuring at low windvelocities particularly in buildings wich have a mechanical ventilation system to create an artificial overpressure. The presence of such a ventilation system however was not a guarantee for sufficient pressure difference over the façade. In later investigations the expectable pressure difference was evaluated first (as far as possible). Measuring at low windvelocity was chosen whenever sufficient pressure build-up by the ventilationsystem was expected.

6.3 The architectural research

The report of the thermographical research was used as starting-point for the architectural research. From this report detailed inspection of the construction of the building was carried out. Parts of the construction were even dismantled if necessary. The dismantling was done as far as possible without damaging the construction and within the available time (which appeared to be insufficient in several cases). Especially those deficiencies which had literally deep-seated causes, could not be inspected. Sometimes caretakers fear of doing destructive research influenced the investigation. Furthermore in a number of cases the available information on the buildingdrawings appeared not to conform with the reality. Details were probably adjusted during the construction of the building and were not worked into the revision-drawings. The architectural research was held to search for:

- the cause of temperature differences,
- the architectural cause of detected deficiencies,
- information to remedy or prevent such deficiencies.

The results of the investigation was reported together with the thermograms made in the thermographical research. A general report for the entire building was sufficient at systematically occuring deficiencies.

6.4 Simultaneous measuring of airtightness and thermographical analysis

The airtightness of a façadefragment was determined in three of the investigated buildings. Simultaneously thermography on the outside of the façadefragment was carried out. These thermographical recordings, made during the airtightness tests, have been worked out quantatively. The concerning pictures, recorded on a video-tape were digitized for a quantative working-out. Calculations can be performed with this

digitized picture on the screen. The surface, the average temperature difference and the integral of product of temperature difference and surface have been calculated for quantitative evaluation of airleakage patterns.

7 ABILITY TO DETECT AIRTIGHTNESS DEFICIENCIES WITH THERMOGRAPHY

7.1 Recognizing of temperature differences

Only the temperature differences which according to the interpretation are connected with airleakage are mentioned in the thermographical research reports. Almost all these probable leakages have been architecturally examined. One or two locations for research were sufficient with systematically occurring temperature differences. If no airleakage could be found, other reasons for temperature differences were looked for. Other possible reasons might be:

- a local higher indoor temperature,
- a thermal bridge,
- an insulation deficiency.

The last possible cause for temperature differences has not been detected. The number of reported differences and the number and percentages of the causes mentioned above are listed in table 3.

building	number of differences	air-leakages number %	thermal bridges number %	increased Ti number %	unknown number %				
WVC-M, Rijswijk	9	7	78	2	22	-	-	-	-
Belastingkantoor, Alphen	12	8	67	1	8	1	8	2	17
Centr. Belastingk., Utrecht	17	9	54	-	-	4	23	4	23
WVC-A, Leidschendam	8	6	75	-	-	2	25	-	-
WVC-B, Leidschendam	7	4	57	3	43	-	-	-	-
Luchtmachtstaf, Den Haag	20	19	95	-	-	-	-	1	5
Rijksluchtvaartschool, Eelde	17	8	47	-	-	-	-	9	53
RIB, Zwolle	15	7	47	4	27	2	13	2	13
Rijksbel., Amstelveen	11	9	82	1	9	-	-	1	9
Kantongerecht, Amsterdam	13	5	38	1	8	4	31	3	23
RKG, Zwolle	14	14	100	-	-	-	-	-	-

Table 3 Distinction of the detected temperature differences with the detected causes.

About 67 % of the reported differences from the thermographical research appeared to be caused by airleakages. In 14 % of the differences the cause remained unexplained and 18 % appeared not to be the result of airleakages.

7.2 Detection of airtightness deficiencies

If all locations of airleakage in the investigated buildings indeed have been detected cannot be evaluated correctly from this investigation. It would be necessary to make an inventory of the buildings in a complete other manner concerning airleakage. If circumstances for thermographical research are favourable, one can start from the

case that also small airleakages can cause temperature differences. In such circumstances, systematically occurring deficiencies will not be missed. Once-only occurring airleakages can be missed easily. However these are of less importance in the whole airleakage of a building.

8 ABILITY OF QUANTIFICATION OF AIRLEAKAGE

8.1 Theory

In the research for possibilities of thermography for quantification of airleakages three flowtypes are distinguished in possible airleakages:

- free flow,
- unilateral limited flow,
- flow to a cavity.

The following theoretical approach has been set up for the flow-principle to a cavity. A steady state situation is presumed. The temperature of the air flowing into the cavity is supposed to be equal to the indoor-temperature T_i . The heat-current inwards is neglected, which is justifiable when there is insulation material on the outside of the inner cavity wall. This is mostly the case. The air flowing from the leakage releases its heat to the outer cavity wall and through the outer cavity wall to the atmosphere. At some distance from the leakage the temperature of the air flowing from the leakage reaches the same temperature as the cavity-air. In its turn this will almost be equal to the temperature of the outer cavity wall. As a result of the airleakage an increase in heatflow through the outer cavity wall develops on a certain area, which can be detected as a higher surface temperature. This additional heat-current Q_{ad} can be phrased as follows:

$$Q_{ad} = \alpha \cdot (T_a - T_o) \cdot A$$

Where:

- α the sum of the transfercoefficient for convection and radiation between atmosphere and outer cavity wall ($W/m^2.K$)
- T_a the average temperature of the temperature differences (K).
- T_o the temperature of the outer cavity wall with no airleakage (K).
- A the surface of the temperature differences (m^2).

The airflow that enters the cavity supplies this heat. The additional heat-current can therefore also be phrased as:

$$Q_{ad} = V \cdot c \cdot (T_i - T_o)$$

Where:

- V the volumecurrent (flow) of indoor air (m^3/s).
- c volminous heat capacity of air ($J/m^3.K$).
- T_i the temperature of indoor air (K).
- T_o the temperature of the outer cavity wall with no airleakage (K).

From both equations follows:

$$V = (\alpha \cdot (T_a - T_o) \cdot A) / (c \cdot (T_i - T_o))$$

The integrated temperature difference $(T_a - T_o)$ can be deduced from the thermogramme. The transfer coefficient can be estimated from the wind velocity and -direction. The temperature of the outer cavity wall can be determined with a contact thermometer, or with thermography apparatus with regard to the air temperature. So the volume current of the air flowing from the leakage can be deduced from the integrated temperature difference and additional data. This approach is reasonable if the heat resistance from the cavity outwards is smaller than the heat resistance from the cavity inwards.

With heavier outer cavity walls the final temperature of air flowing outwards is not equal to that of the outer cavity wall, and the additional heat current inwards can also be larger. Also if the air from the leakage reaches outside with a temperature which is higher than that of the cavity air this approach is not applicable because the amount of heat reaching the outdoor air remains unknown.

When air leakage is of the 'free-flow type', at low velocities there is a connection that makes calculation of airflow possible. The connection is lost at increased air velocity.

A theoretical deduction for unilateral limited flow has not been further developed within the scope of this pre-investigation.

8.2 Quantification from thermographical recordings

The thermographical recording is recorded on analogue video-tape. This tape can be played on a video-recorder connected to a computer. Every recording can be digitized and drawn into memory-banks of the computer. The digitizing occurs in a capacity that no detail recorded on the original tape is lost. Once the picture is available in numbers, calculations can be performed. One possibility is classifying the numbers represented in the picture. Every class has its own colour, up to six colours plus black and white, each colour representing a temperature range. A reproduction can be made by means of a colourprinter.

Thermographical recordings have been made at each step in the increase of pressure during the airtightness tests. The integral of temperature times surface has been calculated in these recordings. A reference should be available when comparing different recordings because they only reproduce temperature differences with regard to an adjustable level. The temperature of the reference may not be influenced by occurring airleakages. A number concerning the airloss through the façade part can be deduced from the quantitative working up of two pictures recorded in different pressure situations. Quantification of airleakage can only be carried out for buildings with mechanical ventilation while at least two recordings at different pressure situations are necessary.

The previous mentioned deductive formula is used for calculation of the airflow through the facade. It is assumed that all air flowing from the leakage releases its heat to the construction before mixing with the open air. Naturally this is an approach. The calculated airloss undervalues the actual airloss. The amount of calculated flow will be equal to or smaller than the actual flow while free-flow and unilateral limited flow is underestimated.

In figure 4 and 5 there are graphs in which the airflow by measuring is plotted together with the calculated values according to the previous described method of thermography.

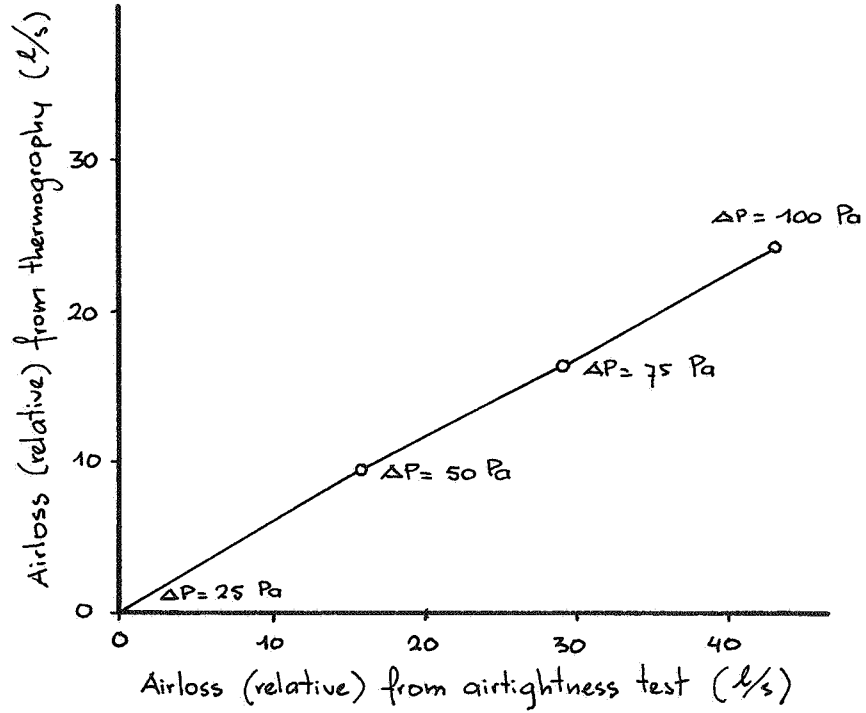


Fig.4 Measured airflow from airtightness test vs. calculated airflow from thermography, building 1.

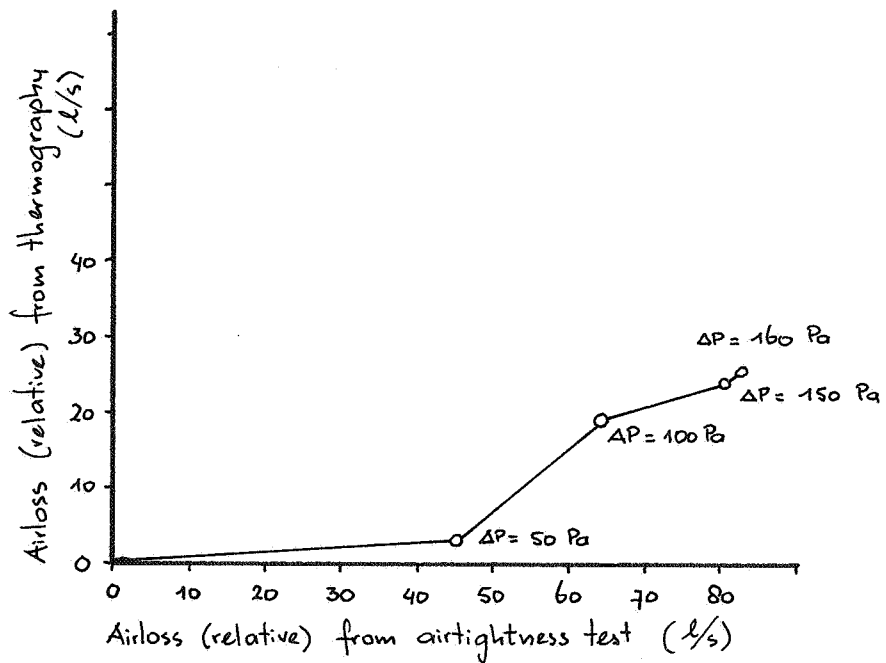


Fig.5 Measured airflow from airtightness test vs. calculated airflow from thermography, building 2. The first step in pressure build-up doesn't produce temperature differences. The cause of this lies in poorly controllable indoor temperatures. Furthermore the calculated airflow is much lesser than the measured flow because not the whole surface of the temperature difference is digitized.

A systematical framework has been developed in which the detected deficiencies from the architectural research according to location and number, together with potential additional information can be classified, in aid of architectural analysis. (Figure 6)

A classification in open and closed elements of the outside wall was chosen. This classification is almost analogue to primary and secondary elements according to the Sfb classification. "The secondary elements in outside walls (Sfb 31) are windows, doors and window-frames, made of wood, steel, aluminium or synthetic material, applicable in outside walls of buildings." This classification offers prospects to unequivocally indicate airleakages at three locations on the building surface:

- in the open façade parts,
- on the deviding line of open and closed façade parts,
- in the closed façade parts.

Furthermore a distinguish was made in the following types of deficiencies:

- Design deficiencies.
Design deficiencies originate in the planpreparation- and materialization phase of the building. Often insufficient insight in the manner in which airtightness must be accomplished is the cause of this. Beside this, wrong choice of materials can result in airtightness deficiencies.
- Construction deficiencies.
Deficiencies during the construction often originates from neglect or carelessness. There is a relation, however, between complexity of specification and chance of construction deficiencies. Many joints or different materials for instance in a construction detail increases the danger of construction deficiencies.
- Maintaince deficiencies.
Deficiencies during maintainance of a building can also cause insufficient airtightness. These deficiencies can be summarized as overdue or not systematic maintainance.

Naturally this distinguish is somewhat arbitrary. An incorrectly sealed joint can be the result of an incorrect tolerance during the design, so that maintainance problems originate sooner than expected. An incorrect chosen sealing during the design can give problems with attachment during construction etc.

10 CONCLUSION AND RECOMMENDATIONS


10.1 Use of thermography for detection of airtightness deficiencies in buildings.

- The circumstances for thermographical research, as set in this pre-investigation (see 6.2.1) seem to be satisfactory.
- About two/third of the temperature differences wich were interpreted as airleakages indeed showed to be caused by airleakage. Hereby the cause of 14 % of the differences is still unexplained. If all locations of airleakage will be detected by thermography cannot be evaluated correctly from this investigation. Nevertheless thermography is very useful in qualitatively examining airleakage of a whole building envelope.

Gebouw : Luchtmachtstaf, Binckhorsthoof fase II
 Binckhorstlaan 135
 15-Gravenhage

bouwjaar : 1984
 geveltype :

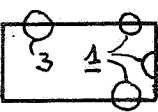
lekken in open geveldelen

	<p>2 doorvoer bediening zonnwering</p>
---	--

detailprobleem

detailprobleem	ontw	uitv	ond	lektype
2 geen afdichting	-	X	-	

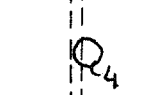
lekken op de grens van open en gesloten geveldelen

	<p>1 kozijn/metselwerk 3 stalen kozijn (glas in lood) op constructie</p>
--	---

detailprobleem

detailprobleem	ontw	uitv	ond	lektype
onjuiste hoekoplossingen en holle afdelprofielen	X	-	-	
afdichting niet aangebracht	-	X	-	

lekken in gesloten geveldelen

	<p>4 kolom/beplaatte gevel</p>
---	--------------------------------

detailprobleem

detailprobleem	ontw	uitv	ond	lektype
? onjuiste afdichting				

Fig. 6

Sample sheet for cataloging the detected deficiencies.

- From quantitative working-out of two thermogrammes taken under different pressure-situations, an estimate can be made of the airloss through a façade-part. This calculated airloss underestimates the real airleakage. For performing this calculation the following extra information is necessary:
 - . pressure-differences over the façade-part,
 - . in- an outdoor airtemperature,
 - . windvelocity and -angle.
 Results of airloss calculation by means of thermography as this moment are not satisfactory. Only when calculated airlosses are less than according to the guide-lines they are useful.

- It deserves recommendation to detect airtightness deficiencies supported by thermography, especially with large and complex buildings. By means of thermography, it is relatively easy to qualitatively examine the entire envelope of the building, which is otherwise impossible or extremely expensive. After this, on grounds of thermographical recordings, specific architectural research or airtightness tests can take place. Guide-lines for an eventual standard research- or evaluation procedure are as follows:
 - . analysis of building-drawings with regard to critical construction details.
 - . decision for qualitative application of thermography on grounds of this analysis.
 - . analysis of thermographical recordings on locations and frequency of air-leakages.
 - . specific inspection by means of architectural research and/or airtightness measurements.

10.2 Recommendations on grounds of architectural research

- For an important part the detected deficiencies can be explained by lack of knowledge. Prevention of airtightness deficiencies starts with instruction and education. This applies to all three types of the detected deficiencies (design-, construction- and maintenance deficiencies). Some elements of instruction and education are mentioned:
 - . principles of reliable airsealing,
 - . systematical errors often have serious consequences for an entire project,
 - . influence of wear of sealants on airtightness,
 - . aged and mudhaven sealings besides waterleakage often also have airleakage.

- The following recommendations can be mentioned on grounds of the detected deficiencies which cause lies in the phase of the building design.
 - . Extra attention should be paid to prevention of airleakages when considering 'special' detailing in façades, especially with in- or outdoor ceilings which hide façade-parts.
 - . The appliance of hollow window-frames or window-profiles and concave 'cope-laths' can give cause to airleakages at unexpected locations when poorly sealed.
 - . The manner of sealing of window-frame systems should be chosen, next to all other requirements, in view of airtightening.
 - . At unsuspectable (small) openings in façades, airleakages can easily originate. (for instance a small opening for operation of sun-blinds)
 - . It is recommended to carefully evaluate a design on airtightness, for design deficiencies often display systematical characteristics. Problems with airtightness occur therefore in the entire building, and not in an incidental detail. Costs of adjustments afterwards often are considerable.

- It is desirable to pay attention to critical details with regard to airtightness during the construction. So-called 'forgotten' and incorrectly placed sealings might be decreased by instruction of the constructional workers and the constructional foreman.
- It is desirable that the management and maintainance of buildings refers to preservation of airtightness. Systematic maintainance implies regular inspection of sealings of cracks and seams.
- The classification of airtightness deficiencies used in this research deserves the recommendation to further develop such an instrument. In this way information is easily transferred and interpretable. At the same time it is an instrument to advance knowledge build-up on airtightness deficiencies.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 6

DRAUGHT MEASUREMENTS IN VENTILATED
AND NON-VENTILATED BUILDINGS

DR. E. MAYER

Fraunhofer Institut für Bauphysik
Institutsbereich Wärme/Klima
(Leitung: Prof.Dr.-Ing.habil. K.A. Gertis)
Postfach 1180
D-8150 Holzkirchen 1
B.R.D.

SYNOPSIS

Measurements of the air temperature and air velocity were carried out in four buildings without air-conditioning using a newly developed anemometer whose sensitivity allows the examination of the dynamic behaviour of air movements. Recent results describing the physical reasons of draft problems were employed in order to re-examine the correlation between air movements and draft problems in a building. From the resulting evaluation criteria follows that besides, the environmental temperature and the mean air velocity, the magnitude of the turbulent fluctuations is important. Measured with these criteria the air movements of all buildings without air-conditioning lie within the range of thermal comfort. The air movements in most of the buildings with air-conditioning lie also in the range of thermal comfort, however, almost half of the values lie within the range of thermal discomfort or in the transitional range. This result coincides almost entirely with the results from questionnaires about the thermal comfort in the tested buildings. The number of complaints about draft problems is significantly higher in air-conditioned rooms than in rooms without air-conditioning.

1. BACKGROUND OF INVESTIGATIONS

The following has been stated in the frame of a German representative survey [1] : In air-conditioned buildings there are significantly more complaints about discomfort and health problems than in not air-conditioned buildings - and this clearly in relation with draft phenomena. To verify this statement in field research, inquiries have been made in comparable collectives in several buildings with and without air-condition and simultaneously a physical analysis of the respective indoor climate.

2. REALIZATION OF INVESTIGATIONS

2.1 Objects investigated and time of measurements

Researches were made in ten different buildings, partly with repeated measurements at different times. Table 1 contains a list of objects, mentioning the equipment with air-condition, the exact times of measurements

Object measured	with air-cond.	without air-cond.	Time of measurement	Outdoor air temp. daily mean value in °C
Bezirksamt Wedding old and new buildg. Berlin		x	December 1983	0,5
Bezirksamt Steglitz, Berlin	x		December 1983 July 1984	0,0 12,0
1. Oberschule Wilmersdorf, Berlin	x		December 1983 July 1984	-1,0 12,0
Kopernikus Oberschule Steglitz, Berlin	x		July 1984	14,0
Siemens-Gymnasium, München	x		March 1984	-1,0
Sophie-Scholl-Oberschule, Schöneberg, Berlin		x	July 1984	12,0
Grasser-Gymnasium, München		x	March 1984	-2,5
Arbeitsamt, Heidelberg	x	x	April 1984	6,0
Konzertsaal, München	x		July 1984	17,0

Table 1: Survey of objects investigated, mentioning measuring time and daily mean value of outdoor air temperature.

The outdoor air temperatures were given by the German Weather Service (Deutscher Wetterdienst).

and the respective daily average values of outdoor temperature. The indoor climate systems are in all cases induction systems with ceiling air outlets. Most of the measurements were made in offices and class rooms, in one case in a big, air-conditioned concert-hall with 630m² of basal surface and about 11m height.

The measurements were made during several periods "typical" for climatization of rooms: winter (December 1983), transition time (March and April 1984) and summer (July 1984). Basically the rooms were tested without occupation, in case of the concert-hall with and without orchestra.

2.2 Measuring instruments used

2.2.1 Anemometer

To make an exact analysis of air movements in living quarters, it is necessary to measure air velocities with high resolution, non-directional and fast, since air movements are subject to permanent variations. Until recently, non-directional measuring of air velocities (not applying here) of 0 m/s to 0,5 m/s was practically impossible [2]. The reason herefor was a usually high temperature of the anemometer sensor of more than 100°C. The self-convection produced with downward current at a velocity of up to 0,1 m/s an ambiguous (that is to say not useable) measuring signal and compared to the ascending current not tolerable differences of measuring signals (fig. 1, top). Only with the developed anemometer working with comparatively low sensor temperature of about 40°C [3] it is possible to make non-directional measurements of low air velocities (fig.1 bottom). In paragraph 3 it is shown that especially fast changing of directions and amount of air velocity are the physical cause of draft phenomena. Therefore, a further essential requirement to an anemometer is a short time constant. The newly developed anemometer corresponds to this requirement with a time constant of 10 m/s (fig. 2).

2.2.2 Air temperature measuring device

To measure the air temperature, a customary resistor thermometer was used.

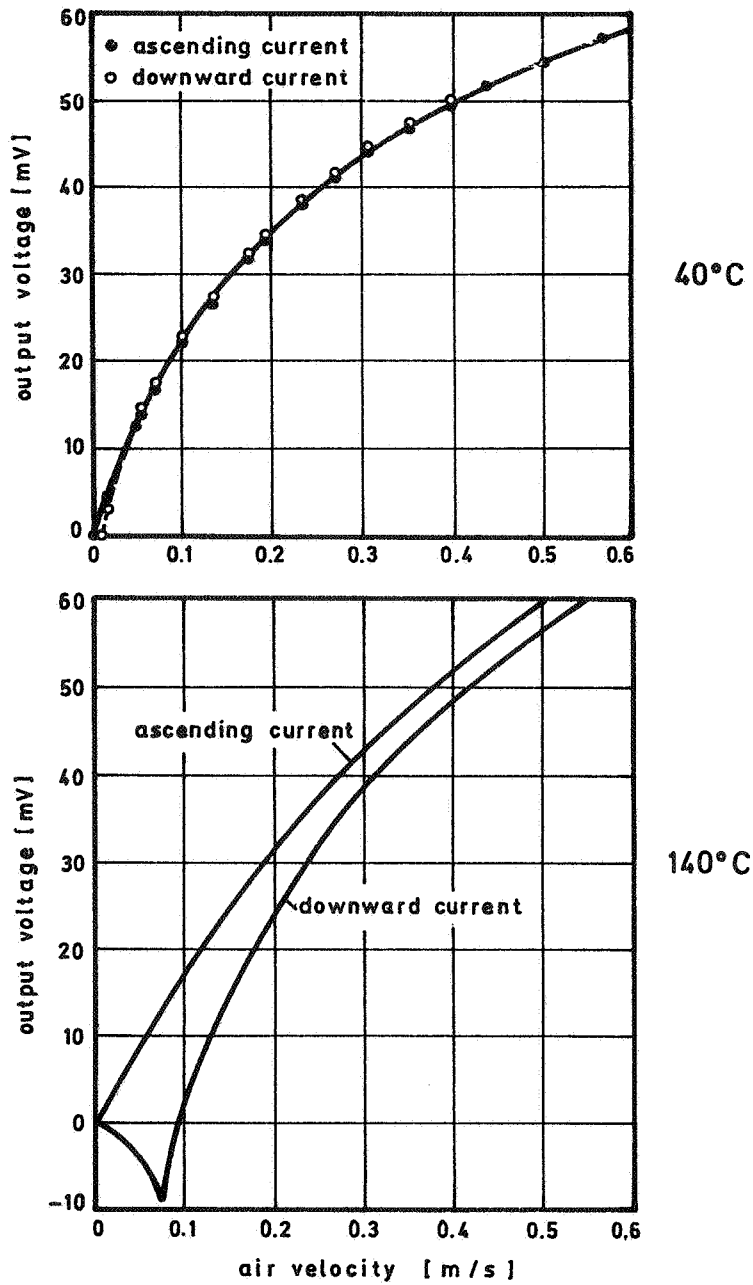


Figure 1: top: Calibration curves of a constant temperature anemometer heated up to c. 140°C.

bottom: Calibration curves of a newly developed anemometer heated up to c. 40°C, for ascending and downward air streams.

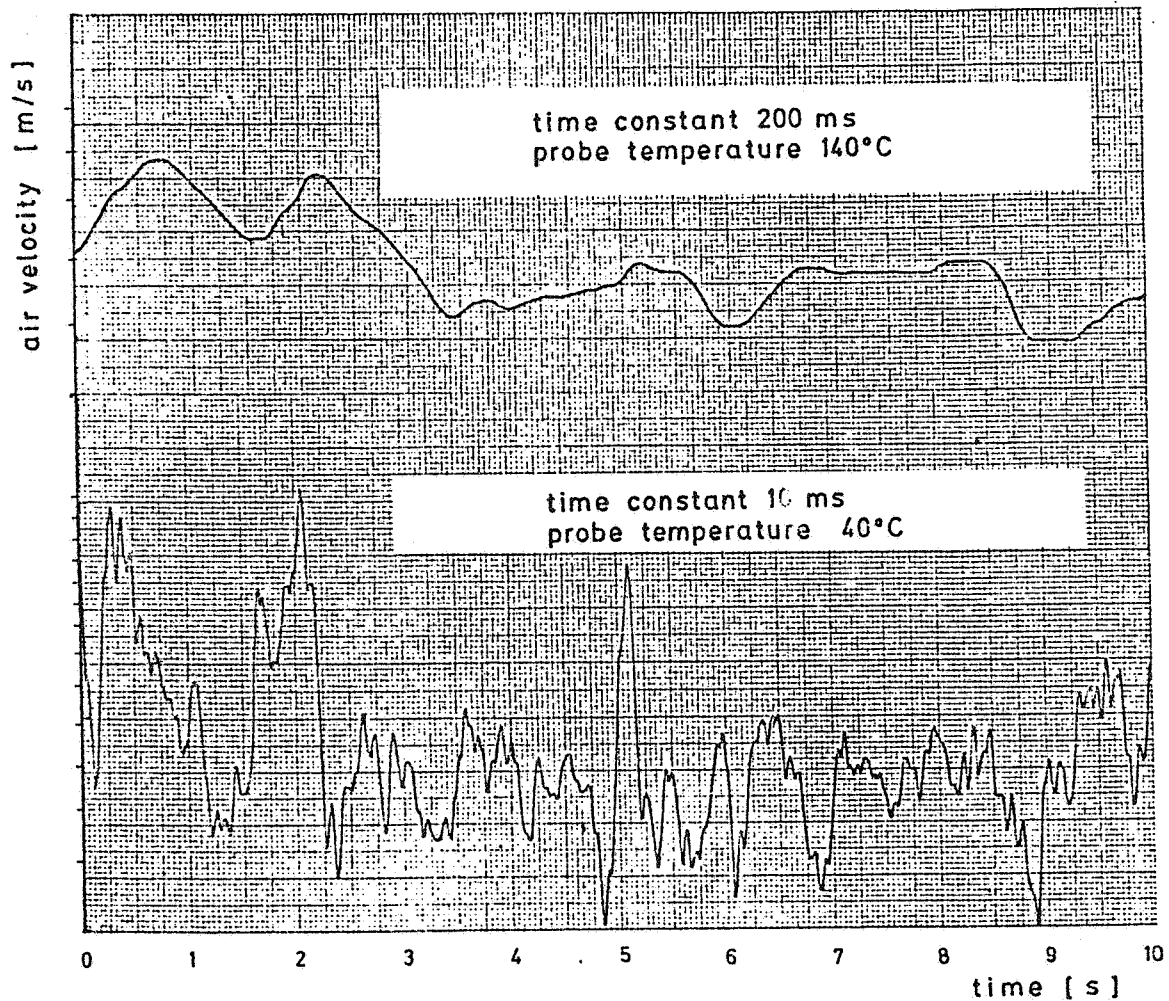


Figure 2: Anemometer measuring signals registered at the same time and at the same place with differing time constant.
top: older anemometer same as in fig.1 top
bottom: newly developed anemometer same as in fig. 1 bottom.

2.3 Registration of measuring values and evaluation

In the tested rooms those spots were chosen for measurement where persons stayed. In these areas measurements of air velocity and air temperature were generally taken in three levels above floor level:

0,2 m, about height of ankles

1,3 m, about height of head when seated

1,8 m, about height of head when standing.

For statistic evaluation of air velocity measurements, the measuring signals are lead to a classifier and are scanned - always during c. 5 min. - in intervals of about 0,3 seconds. The relative cumulative frequency per velocity class can then be read off. These are registered in a Gauß probability paper (fig. 3, top). In a Gauß normal distribution of air velocity, the entered measuring points must be in a straight line, which was the case here. From the probability paper the corresponding air velocity mean values (50 % values) and the standard deviation (difference between 84 % and 50 % value) can be read off. The quotient of these two values is called turbulence intensity and in combination with the average value is used to judge draft phenomena (see par. 3). Both values are shown in the diagram in fig. 3, bottom.

3. EVALUATION OF RESULTS

Aim of the present researches is an evaluation of the stated air velocities with regard to draft phenomena. As mentioned above, the mean value of air velocities as well as the turbulence thereof are essential. This is explicitly explained in [4] and presented briefly in the following.

3.1 Evaluation of results considering mean value and turbulence of air velocities

When evaluating the air velocity, we presume that "draft" exists from the moment when the convective loss of heat of man becomes as great as to be disagreeable and/or the surface temperature drops too low. From the physical point of view, the convective surface-heat-transfer coefficient and the surrounding temperature are responsible herefor.

In the cited report [4], first measurements at a heated artificial head with air stream to the front show a parabolic relation between product of mean air velocity

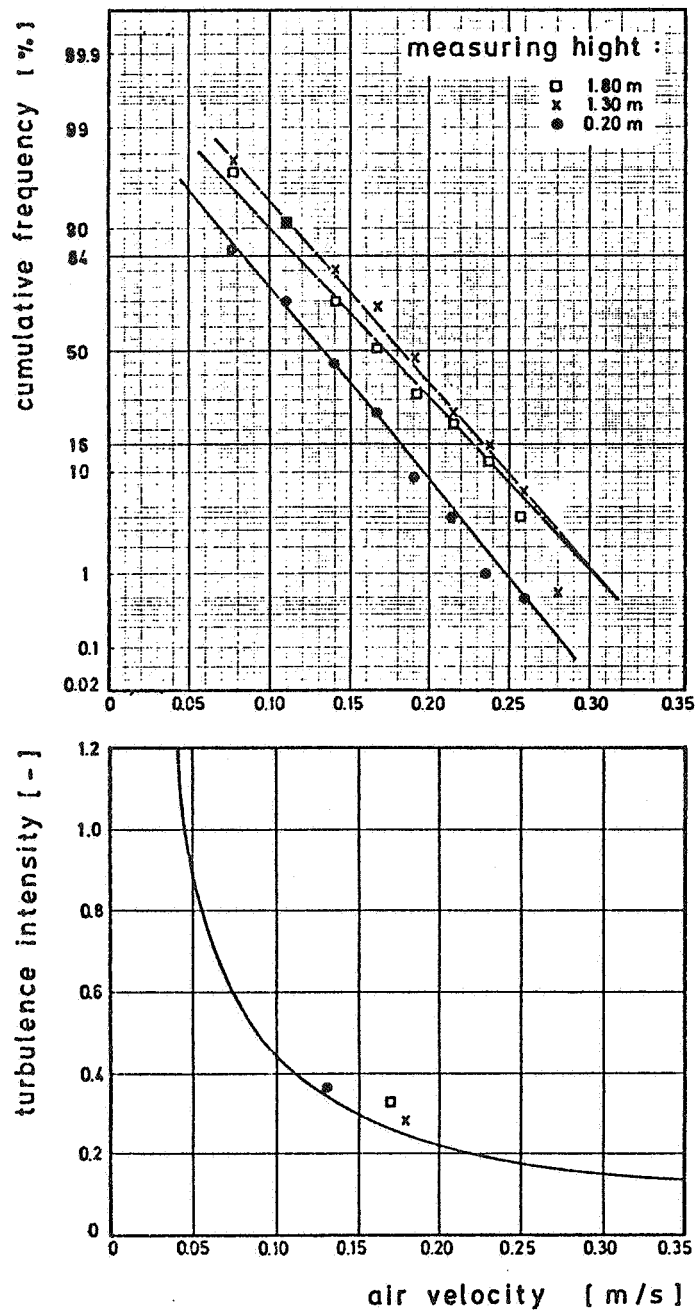


Figure 3: Cumulative frequency and turbulence intensity of air velocities measured in a room. The hyperbola from the bottom figure can be taken from figure 5, in this case a surrounding temperature of 21,5 °C.

and turbulence intensity on the one hand and the convective loss of heat (surface-heat-transfer coefficient) on the other hand (fig. 4). Taking further into consideration

- former exemplary indoor climate measurements in air-conditioned offices and clean rooms, where, for 22°C surrounding temperature a maximum admissible surface-heat-transfer coefficient of about 12 W/m²K was found [4] (dotted line in fig. 4), as well as
- the heat balance equation for dry heat loss presented in [4] ,

figure 5 can be derived. In this diagram there are - similar to fig. 4, bottom - the maximum admissible values of the convective surface-heat-transfer coefficient for the different surrounding temperatures (top margin of fig.). The curves are hyperbola, since the coefficients according to figure 4 are determined by the product of turbulence intensity and mean air velocity (right margin in fig. 5).

A comprehensive presentation of all measuring results and evaluation is shown on figure 6, top. By means of the relation shown in figure 4, the respective convective surface-heat-transfer coefficients can be computed from the values of mean air velocity and turbulence intensity. In figure 6, top, the convective surface-heat-transfer-coefficients are registered with the measured surrounding air temperatures. Distinction is made between values measured in air-conditioned and unair-conditioned buildings. Furthermore, an evaluation curve is drawn, limiting the top of still comfortable (free of draft) combinations of values. This curve is easy to be derived from figure 5.

It is obvious that the values measured in unair-conditioned rooms are lower than those in air-conditioned rooms. In the "comfortable" range (below the limiting curve) lie almost all values of unair-conditioned rooms. Not quite half of the values of air-conditioned rooms are in the "uncomfortable" range, many in height of the limiting curve, some even higher. For unair-conditioned the convective surface-heat-transfer coefficients rooms ranged between 7 W/m²K and 10 W/m²K, average about 8,5 W/m²K; for the air-conditioned rooms c. between 7 W/m²K and 15 W/m²K, average about 11 W/m²K. This result coincides with the results of investigations in the tested nine objects, saying that in rooms with air-condition there are considerably more complaints about draft than in rooms without air-condition.

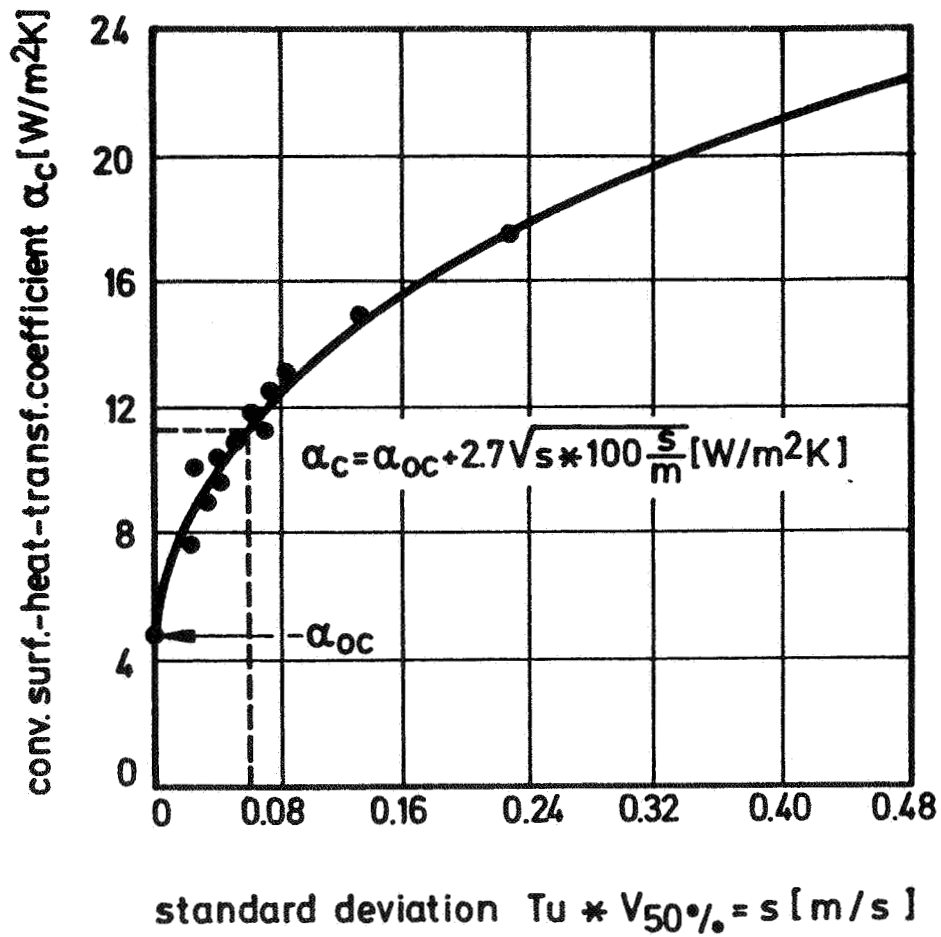


Figure 4: Measured correlation between convective surface-heat-transfer coefficient and the product of turbulence intensity and mean air velocity, i.e. the standard deviation of air motion (dots), as well as computed correlation.

- α_K : convective surface-heat-transfer coeff.
- s : standard deviation
- α_{EK} : convective surface-heat-transfer coefficient with self-convection.

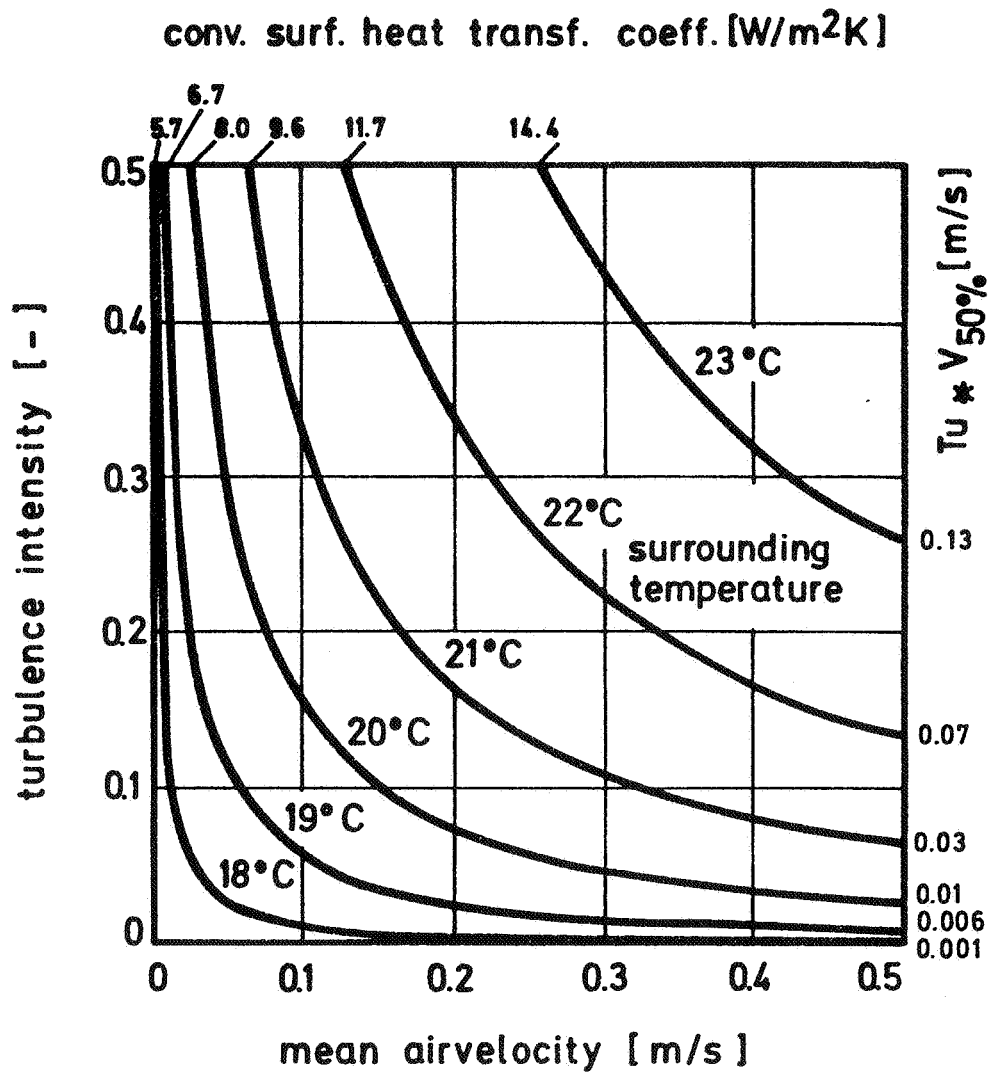


Figure 5: Correlation between turbulence intensity and mean air velocity in different surrounding temperatures. At the top margin of the figure there is the maximum admissible convective surface-heat-transfer coefficient presented in different surrounding temperatures, found on the basis of provisional measuring results in 1 .

$v_{50\%}$: mean air velocity or 50 %-value

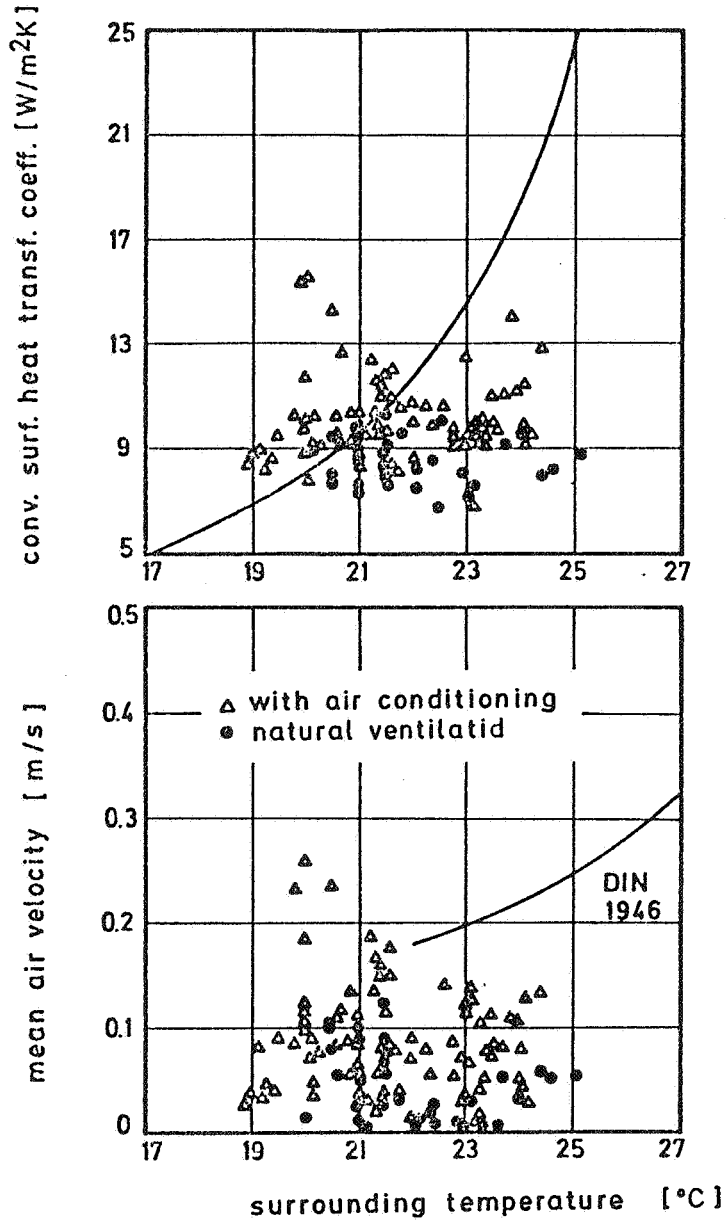


Figure 6: top: Convective surface-heat-transfer coefficients depending on surrounding temperatures, as well as evaluation curve acc. to figure 5.

bottom: Mean air velocities and surrounding temperatures, as well as evaluation curve according to DIN 1946, part 2 [4].

Complaints about draft, more frequent in summer, can be explained by the aid of figure 6. Presuming that the convective surface-heat-transfer coefficients remain basically independent of the season - the present results are confirming this - the air temperature e.g. 18°C, the maximum admissible value of 6 W/m²K (fig.5) is surpassed in any case. However, air temperatures of 18 ° C in the area of air outlets must be expected in summer.

3.2 Evaluation of results according to DIN 1946

The usual evaluation of air motions according to DIN 1946, part 2 [5] depends solely on the average air velocity and air temperature. In figure 6, the measured values and the evaluation curve according to DIN are entered in a corresponding diagram.

It can be stated that the measured values in the range of the DIN-curve, i.e. above 22°C air temperature, are admissible - in accordance with figure 6, top. All measured values with air temperatures below 22°C would be "forbidden" according to the curve. Since almost half of all measuring values are within this range of temperature, the present DIN-evaluation curve does not seem appropriate for practice. If the DIN-curve was continued to the bottom with constant incline, almost all measuring points would lie below the extended curve. This would show a more optimistic evaluation than following the curve in figure 6 top.

4. SUMMARY AND CONCLUSIONS

Measurements of air velocity and air temperature were carried out in four objects with air-condition and in six objects without air condition. The measurements were made in 60 measuring spots, in the height of 0,2 m (ankle), 1,3m (head when seated), 1,8 m (head when standing). A newly developed anemometer was used here which especially permits to analyse air motions regarding their dynamic behaviour. New test results (some still to be completed) describing the physical causes for draft phenomena were employed to examine the causal correlation between air motion and draft phenomena. Resulting evaluation criteria showed that besides the air temperature (surrounding temperature) and the temporal mean value of air motion, the turbulence intensity as well is decisive for draft phenomena.

Measured with these criteria practically all air motions in buildings without air-condition are within the comfortable range. The majority of air motions measured in buildings with air-condition is in the comfortable range. Less than half of the measuring values are in the uncomfortable range, many close to the comfort limiting curve, some clearly above. This result coincides with results of other investigations in the tested buildings, saying that in rooms with air-condition there are more complaints about draft phenomena than in unair-conditioned rooms. Other than these new criteria of comfort, the valid DIN 1946 does not consider temporal dynamic behaviour of air velocities. It must be added, that according hereto, air temperatures below 22°C would not be admissible.

Further steps have to be taken to eliminate complaints in air-conditioned buildings and from the present investigations the following conclusions can be drawn:

- 4.1 The criteria used up to the present for evaluation of air velocities are incomplete.
- 4.2 The dynamic behaviour of air motions (turbulence) must be taken into consideration.
- 4.3 Due to the physical test results, it seems more reasonable to apply the convective surface-heat-transfer coefficient than the air velocity as measuring unit for evaluation of draft phenomena.
- 4.4 The physical investigations, including the dynamic behaviour of air motions in rooms, must be completed and subtilized to confirm the provisional marginal comfort values. To this aim also psycho-physical investigations are required. Above all, there must be systematic researches to find out whether draft phenomena are the sole cause for complaints or whether other causes as well (f.i. minor air quality) have any influence.
- 4.5 From the technical point of view we have to find out precisely whether the complaints are due to basic deficiencies of indoor climate installations or, whether the installations do not reach the desired values i.e., whether they are badly serviced and adjusted.

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PAPER 7

DATA NEEDS FOR THE PURPOSE OF AIR INFILTRATION
COMPUTER CODE VALIDATION

J-L. SCARTEZZINI¹, J-M. FUERBRINGER¹, C-A. ROULET¹ & H.E. FEUSTEL²

¹Ecole Polytechnique Federale de Lausanne (EPFL)
1015 Lausanne
Switzerland

²Lawrence Berkeley Laboratory (LBL)
University of California
Berkeley
CA 94720
USA

Abstract

A simplified model of air infiltration has been developed at Lawrence Berkeley Laboratory, in order to expand the use of air flow calculation techniques outside the field of research. The validity of this program must be checked. Benefit have been gained from work dedicated to the same problem in the field of building thermal analysis. Following this idea, a detailed validation methodology is proposed. Progression in the complexity of the modelled structures, use of high accuracy data are sine qua non to this task. Moreover, for a simplified model, an approach based on Monte-Carlo techniques appears necessary. The validation of the developed simplified model will be carried out by way of a joint research project between EPFL and LBL. It is hoped that the validation procedure, proposed in this paper, will be used to validate other air infiltration calculation techniques.

1. INTRODUCTION

Infiltration and ventilation are key factors regarding indoor air quality as well as being utilized for heat transfer through a building. In the past few years, research efforts have been made to acquire accurate knowledge about infiltration and ventilation in single-family dwellings, and more recently in multi-zone buildings [1].

Following this idea, a wide variety of modelling techniques have been developed to cope with the problems of estimating the hourly air exchange rates and flow rates inside the buildings [2,3,4]. Unfortunately, these models are facing the same difficulties as the thermal models were facing a few years ago: the lack of *satisfactory validations*.

Validation is the method of comparing model outputs with a reference and drawing conclusions from this comparison. More specifically, one may be concerned with testing the validity of a model's theoretical basis or its ability to reproduce observed physical phenomena. In the field of building thermal analysis, only a few research teams have conceded a major effort to define a coherent *validation methodology* [5,6,7]. Among them, Bownan and Lomas [5], as well as Anand et al [6], successfully applied such a methodology to building thermal models.

It is the purpose of this paper to outline an adequate validation methodology for air infiltration and ventilation computer programs. Special attention will be paid to the validation of a simplified theoretical model, which has been recently developed at Lawrence Berkeley Laboratory (LBL). A joint research program, focused on this topic and involving collaboration of Ecole Polytechnique Fédérale de Lausanne (EPFL) and LBL, will be presented here.

2. CURRENT AIR INFILTRATION MODELS

A few authors have recently reviewed the different air infiltration techniques, which have been developed during the past decade [2,3,4]. As in the field of building thermal analysis, models vary principally in their complexity, hardware requirements and ease of use.

A convenient way of ranking models, proposed by Burch for building energy analysis [8], can be transposed to the air infiltration problem. Burch suggests that models be categorised according to the level of detail in the building simulation to be investigated. Three levels are identified :

- 1) The mechanism level
- 2) The building level
- 3) The housing level

Models which are able to handle the mechanism level can be used for prediction of air-flow distribution inside the building. On the other hand, models which investigate the building level, will only provide mean air exchange rates. Moreover, programs of the housing level, are only able to model air infiltration characteristics at the level of the housing sector.

The more recent investigations of the Air Infiltration and Ventilation Center (AIVC) in the field of modelling [4] has shown that all reported models belong to the first two categories. The lack of huge air infiltration surveys, carried out on a statistically significant amount of buildings, explain why there are no models of the third kind. Passive measurement techniques [9], which could be a good way to obtain statistics of long term effective ventilation rates, will certainly modify this situation in the future.

1. Empirical methods			
<i>Technique</i>	<i>Data requirements</i>	<i>Avantages</i>	<i>Disadvantages</i>
Air change methods	Basic buildings design details	-Ease of use -No computing facilities required	- Does not provide detailed infiltration predictions
Reduction of pressurisation test data	Pressurisation test data	-Ease of use -No computing facilities required	- Applies only to existing buildings for which pressurisation test data is available - Does not indicate the effects of weather, shielding and terrain conditions
Regression methods	Infiltration measurement data (wind and temperature records)	-Fairly easy to use -Give weather dependent infiltration predictions. -Can give reasonable results.	- Only really applies to existing building in which tracer gas measurements have been performed. - Typical regression data are available but they can give very unreliable results
2. Theoretical methods			
Network models	- Building description - Surrounding shielding data. - Terrain roughness. - Flow path data.	-Predicts air distribution patterns. -Determines internal pressure distribution. -Responds to weather, terrain and shielding parameters. -May be used for combined air infiltration and mechanical ventilation calculations.	- Substantial data may be required to describe flow network. - Considerable computational effort.
Simplified theoretical models	- Air leakage characteristics of buildings. - Shielding data. - Terrain roughness.	-Offers a compromise between the complexity of network models and the inaccuracy of empirical techniques	- Until today only applicable to single zone structures. - Provides no information on the direction of air movement.

Fig. 1 : Summary of the current air infiltration calculation techniques [4].

Figure 1 shows a summary of different calculation techniques of first and second level as reported in Reference [4]. These techniques belong to two categories which are :

- 1) The empirical methods
- 2) The theoretical methods

Empirical methods are generally acting at the building level; theoretical methods on the other hand handles at the mechanism level. In this paper, we will focus out attention on the second kind of methods, which are thought to closely correspond to the possibilities offered by informatics today.

Current theoretical models are generally network models; they describe the building as a flow network in which nodes represent zones of differing pressures, interconnected by air flow paths.

The modelling process, therefore, results in a set of equations, which are completed by the boundary conditions. The latter are given by way of pressure data, expressing the external pressure action on the modelled building.

An iterative method is generally used to solve the system of equations. Reference 10 gives an example of a theoretical network model which uses the exposed approach. Figure 2 illustrates the network model employed to simulate air-flow distribution in a two story multi family building, presented in the same reference.

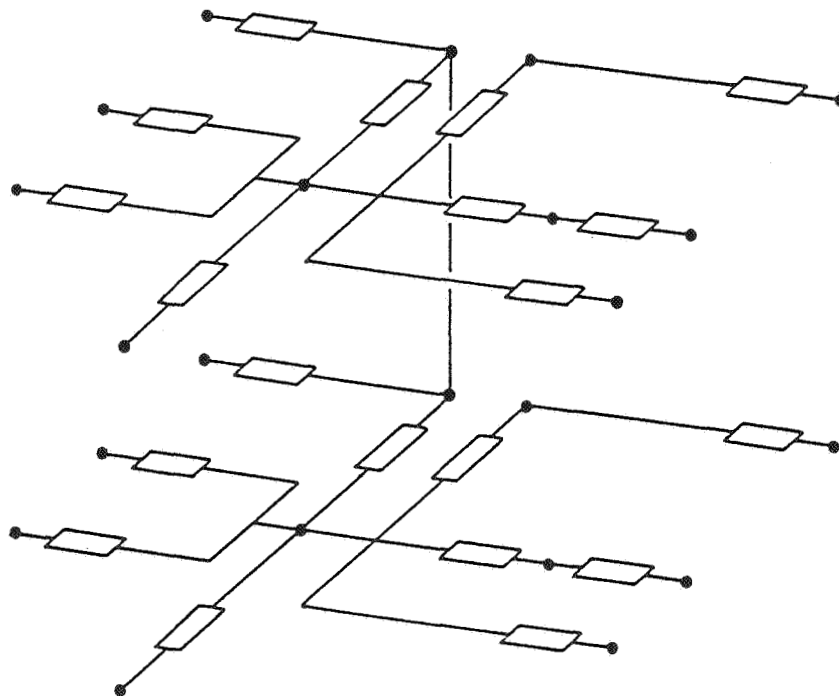


Fig. 2 : Network model used to simulate air-flow patterns in a two story multi-family building [10].

The model parameters generally requested by the network approach are [4] :

- flow path distributions (external and internal)
- flow path characteristics
- building height
- internal / external temperature differences
- wind speed
- local shielding conditions
- terrain roughness parameters
- detail of mechanical ventilation systems

Several theoretical models address the complexity of air-flow in multi-zone buildings [2], but the majority of them are written as research tools. The main challenge when developing simplified theoretical models is to reduce calculation effort, in way to render this method compatible with personal computers and expanding the use of air flow calculation techniques outside the field of research. The forthcoming lines will be focused on such a simplified model, recently developed at LBL [11], and will present this calculation technique.

3. SIMPLIFIED THEORETICAL MODEL

In order to simplify the air flow calculation procedure, following assumptions are taken :

- 1) It is first assumed that all permeabilities have the same flow characteristics (same flow exponent).
- 2) A set of lumped parameters has been defined to describe the permeability of the building.
- 3) Wind and stack driven air flows are calculated separately.
- 4) Overall air flows are obtained by superposing the two contributions

Three lumped parameters, which reflect the different permeability distributions of the building's envelope and flow resistances inside the building are introduced. The envelope permeability ratio epr is used to describe the horizontal air flow through the structure :

$$epr(\phi) = \frac{D_{lee, envelope}}{D_{total, envelope}}$$

Based on a parameter given by the German standard on heat loss calculation for buildings the vpr ratio for the permeabilities from one floor to another and the overall permeability of the building envelope, has been introduced in order to describe the vertical air flow through the building;

$$vpr = \frac{D_{shaft}}{D_{total, envelope} + D_{shaft}}$$

To describe the air-flow distribution for the different zones at the story level, the resultant permeability ratio rpr has been established :

$$rpr(\phi) = \frac{D_{res,zone,lee}}{D_{res,zone,total}}$$

This lumped parameter has been defined as the ratio of the resultant permeability of the downstream side to all resultant permeabilities of this particular zone. It was determined that air flows from zones with low rpr -values to those with high rpr -values.

For wind flow perpendicular to the surface, the pressure difference responsible for the wind- driven air flow can be calculated by :

$$\Delta p_{wind,windward}(z) = p_{dyn}(z) \bar{c}_{wind}(z) - \Delta p_{in}(z)$$

The internal pressure P_{in} is a function of the permeability distribution of the building's envelope and of the internal flow resistances; it can be derived from the continuity equation for each story.

The volume rate driven by wind action only can be calculate by :

$$Q_{wind}(z) = D_{wind}(z) [\Delta p_{wind,windward}(z)]^n$$

In order to avoid calculating the pressure distribution inside the building, a method for determining the air flow path through each of the stories utilizing the story-type building as a base case can be utilized: the latter one is given by Feustel et al [11].

To determine the air flow path through a building for a given wind direction, the floor plan is examined for all possible paths from the windward side to the leeward side of the building. By knowing that air flows from zones with low rpr -values to those with high rpr -values, the flow direction can be determined.

The difference in thermal pressure for a given temperature difference under calm conditions is a linear function of the distance of the height above ground from the neutral pressure level z_n . The volume rate driven by thermal buoyancy alone is :

$$Q_{stack}(z) = sign(\Delta p_{stack}) D_{res}(z) |\Delta p_{stack}(z)|^n$$

$$\Delta p_{stack} = g (\rho_{in} - \rho_{out}) (z - z_n)$$

$D_{res}(z)$ is the resultant permeability calculated for the arrangement of permeabilities, in a series or parallel to the place where the stack pressure occurs.

Air flows caused by the two separate mechanisms can not be simply added because the flow rates are not linearly proportional to the pressure differences. In order to superimpose the flows, pressures must be added. The superimposed volume rate can generally be calculated by :

$$Q_{tot} = D (\Delta p_{tot})^n$$

$$Q_{tot} \approx D (\Delta p_{wind} + \Delta p_{stack})^n = (Q_{wind}^{1/n} + Q_{stack}^{1/n})^n$$

The building parameters required by such a model are thus :

- flow path structure
- air permeability of openings
- temperature difference inside/outside
- wind pressure parameters
- mechanical ventilation parameters

A simplified theoretical model is based, as has been shown in the former considerations, on a significative amount of simplification procedures. These simplifications necessitate by their own the setting up of a satisfactory *validation methodology*. The outline of such a methodology will follow.

4. METHODOLOGY OF VALIDATION

An important outcome of the research projects carried out by Judkoff et al [7] and Anand et al [6] in USA, as well as by Bowman and Lomas [5] in UK, has been to define a coherent *validation methodology* for purpose of buildings thermal analysis models. This validation approach, which appears to be very satisfactory, will be used here to set up a such a methodology for air infiltration simulation programs.

Following the idea of Judkoff, three types of investigatory methods, each designed to reveal errors in the modelling processes can be defined:

- 1) Analytical verification
- 2) Inter-model comparison
- 3) Empirical validation

In analytical verification, the predictions of the model are compared with carefully designed problems with known analytical solutions. This technique is severely limited because of the small range of problems for which exact analytical solutions can be formulated. The latter do, however, provide an exact-truth-model against which the predictions of the model can be compared

In inter-model comparisons, the predictions of two or more models of some hypothetical building are compared. Such studies are sometimes termed "software-software" comparisons. The advantage of these types of studies are that they are simpler and less time

consuming than the other techniques, and any complexity of the building or any climate regime can be chosen. The main disadvantage is that there is no "absolute true" model against which to compare the predictions. References 13 to 14 report such comparisons carried out for the International Energy Agency (IEA).

Empirical validations, sometimes called "software-hardware" comparisons, is the ultimate state in any validation process. Simply stated, empirical validation is the comparison of the predictions of the model with physical reality. This technique has the greatest potential for assessing whether the approximations and operations in the model are adequate to predict the measured air flow characteristics of the building. The potential power of this technique, together with the fact that the process is comparable with those that prevail when the model is used is the analysis process, means that it has been widely used for validating building thermal simulation programs : over 130 validations of this type have been disclosed by Lomas in a recent literature survey [5].

However, even if the empirical validation appears to be the most frequently used method to test the validity of a model, it must be pointed out that sources of error introduce uncertainties in this validation process; these sources of error can be divided into two categories which are [7] :

- 1) The internal errors
- 2) The external errors

Internal errors are due to inaccuracies in the modelling and in the numerical solution techniques adopted by the model as well as due to coding errors.

External errors occur in gathering the model input data, in transferring this data to the model, in monitoring the physical air flows behaviour and in comparing the measured and predicted values.

Figure 3 summarizes the type of errors which are inherent to empirical validations.

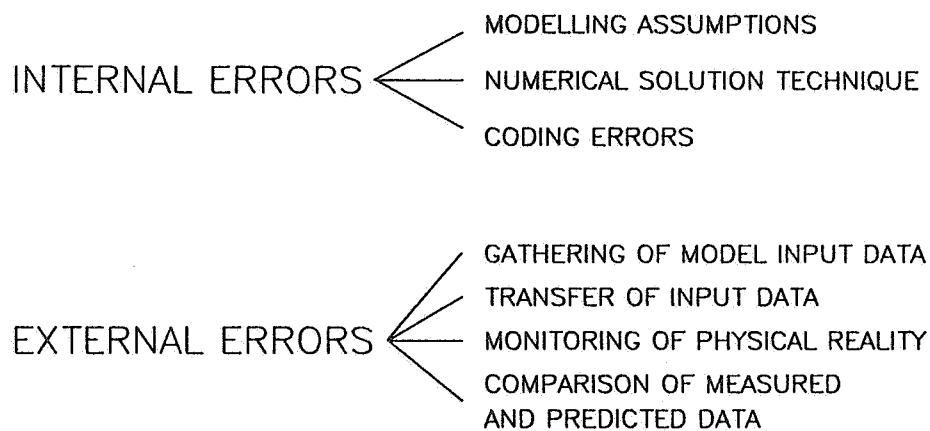


Fig. 3. Sources of errors inherent to empirical validations.

The conclusion which can be drawn from the preceding lines is that empirical validation should only be carried out when using high quality data sets from well known and defined buildings or structures.

The experience gained in the field of building thermal analysis has shown, however, that empirical validation (even when involving high quality data), carried out only on a single building is not satisfactory. The model and algorithms should in fact, be compared to a significant set of buildings and climates, which is, however, a cumbersome task.

It emerges from the study of Bownan and Lomas [5] that satisfactory validations should be proceeded sequentially from simple to more complex situations. Simple situations, involving the more important mechanisms, can be investigated by means of analytical verifications; more rigorous tests must be based on empirical validations, involving high quality monitoring of data from real structures. A progression from a well defined single room, inside a larger temperature and pressure controlled enclosure, to a multi-zone naturally ventilated and multi-story buildings, defines a "sine qua non" way to process a validation procedure.

This approach is however adequate only for theoretical network models, which are mainly found in the research area. When considering simplified models, it has been shown by several authors, that a more complicated validation methodology has to be employed. It has been experienced in the field of thermal analysis that, input assumptions, based on standard engineering references can cause errors in the prediction of the model which can go up to 60 per cent : the determination of the inaccuracies of a simplified model with respect to the designer must, in this way, also be quantified.

The cause of these inaccuracies differ from the simplification procedures inherent to the simplified models. They are mainly due to the following reasons :

- 1) Physical scattering of design parameters
- 2) Impact of randomness of external conditions
- 3) Influence of building users

Figure 4 shows the proposed validation methodology, defined similarly to the one set up by Anand et al in Reference 6. This methodology is intended to be adequate for validation of simplified theoretical methods. Four levels of validation are defined; their purpose is as follows :

- Level 1 : Determination of inaccuracies due to internal errors (network model)
- Level 2 : Identification of inaccuracies due to simplification procedure (simplified model)
- Level 3 : Determination of the inaccuracies of simplified model with respect to the designer
- Level 4 : Field verification of the simplified model

VALIDATION METHODOLOGY

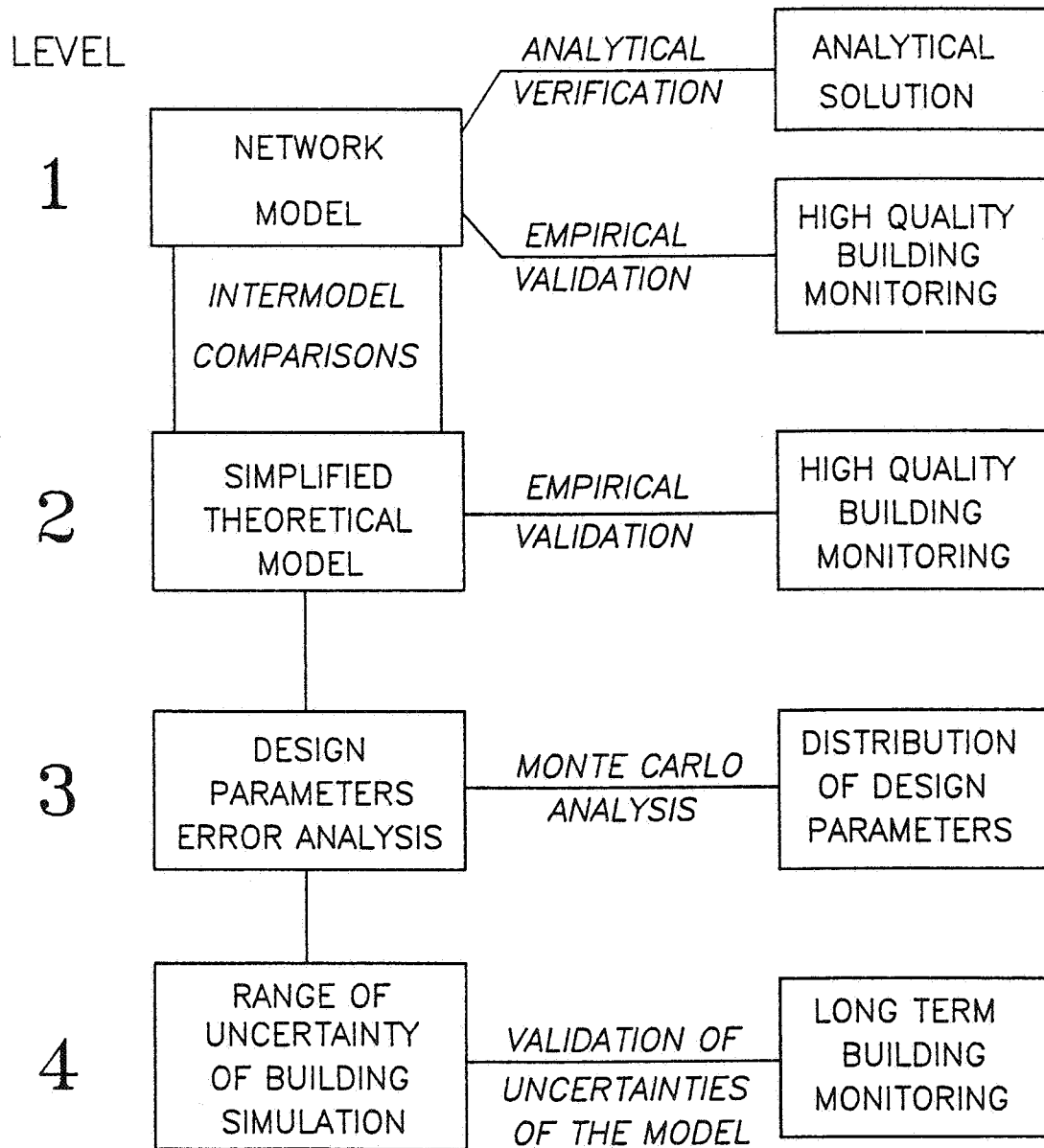


Fig. 4 : Validation methodology for network models and simplified theoretical models following the study of Anand [6].

To perform validation step "level 3", a Monte-Carlo simulation technique has to be used in order to account for the statistical scattering of design parameters (air flow characteristics, external conditions). The other steps involve analytical, empirical and intermodel comparisons. It is expected that a 95 % confidence limit of the predicted variables shall be obtained in this way. These confidence limits will be finally checked at "level 4" validation against the physical reality.

5. FORTHCOMING JOINT RESEARCH PROJECT

It appears obvious that to fulfill the overall proposed validation methodology is a huge undertaking. In a first step, the joint research program between EPFL and LBL devoted to the validation of the LBL simplified model has been limited.

Partial validation of the LBL simplified model will be made following the first etapes of proposed methodology. Progressively more complex structures will be used for this purpose and the two first levels of validations, proposed in Figure 4, carried out on the model.

Two different structures, both located at EPFL, will be used. They are defined as :

- 1) A double-room structure inside a larger temperature and pressure controlled enclosure (CHEOPS facility).
- 2) A mid-sized three-story, multizone experimental test facility (LESO building).

The double room structure (see Figure 5) is intended to be used mainly to carry out analytical verification. The double room is built in such a way that the permeability of the walls, floor and ceiling can be fully controlled. The floor and the ceiling are 8 x 4 x 0.1 m. boxes with a multitude of small holes in the inner panel, to have the possibility to carry out a piston-type ventilation. This double room is enclosed in a thermally insulated box, in which the temperature and several pressure differences can be controlled.

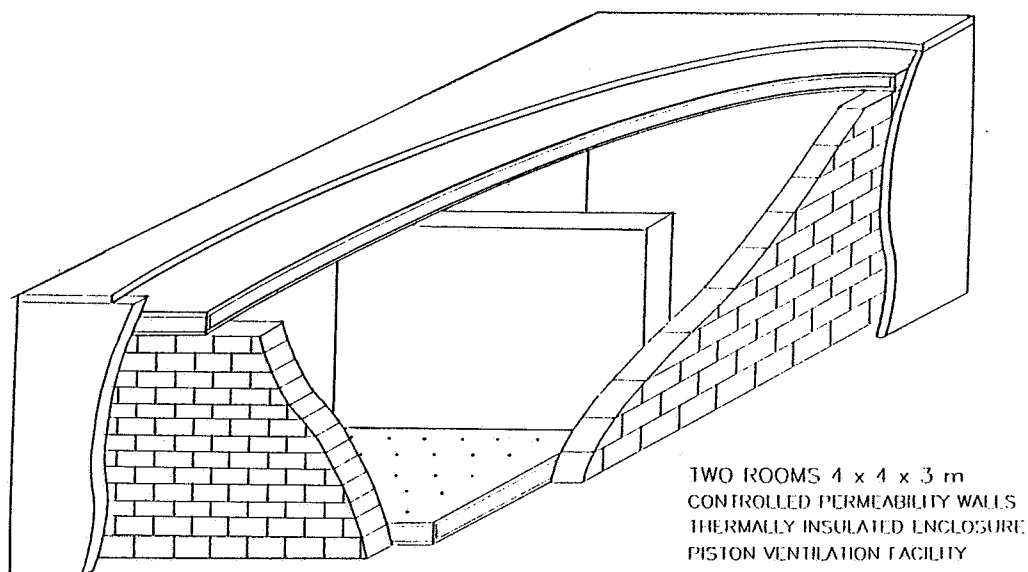


Fig. 5 : View of the double-room CHEOPS facility

The LESO test facility (see Figure 6) has been operating since 1981 on the EPFL campus near Lausanne. It is a mid-sized administrative building with its main façade facing south. Figure 6 provides a view of the building as it appears at the south façade. The main physical characteristics of the facility regarding infiltration are also given in this figure. Nine heavily-instrumented zones make up the south half of the building. Each zone is equipped with a different passive or hybrid solar façade, dependent upon its own air infiltration characteristics. A staircase occupies the other half of the building. The ventilation is provided for the most part by natural ventilation. Only a few of the solar units are equipped with mechanical ventilation systems [15].

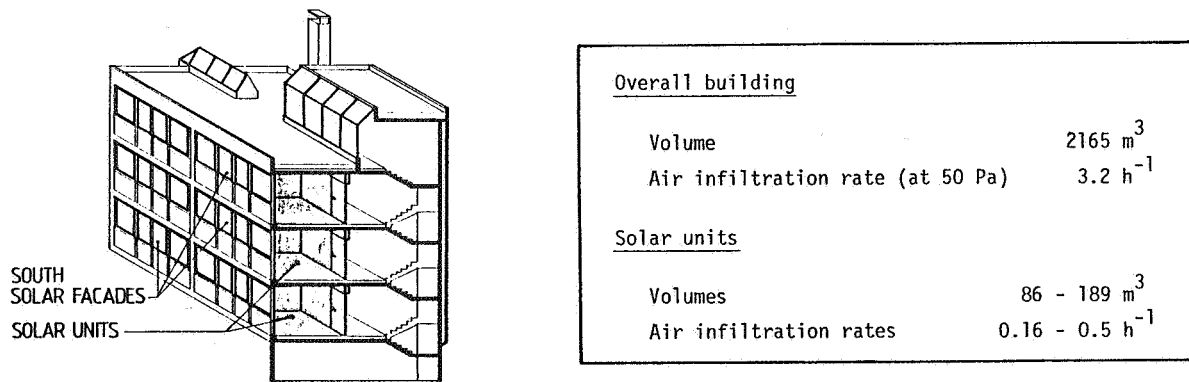


Fig. 6 : Main characteristics and view of the LESO test facility

In order to perform the model validation, input data must be provided to the simplified program. This set of input parameter is composed of the following items :

- 1) Permeability distribution of the envelope
- 2) Permeability distribution of interconnected zones
- 3) Wind pressure coefficients
- 4) Stack parameters
- 5) Mechanical ventilation data
- 6) Meteorological conditions

Figure 7 shows the complexity of the building. The different interconnected flow paths are shown in this figure. The designation of the different zones, which should be considered in the modelling process are also indicated.

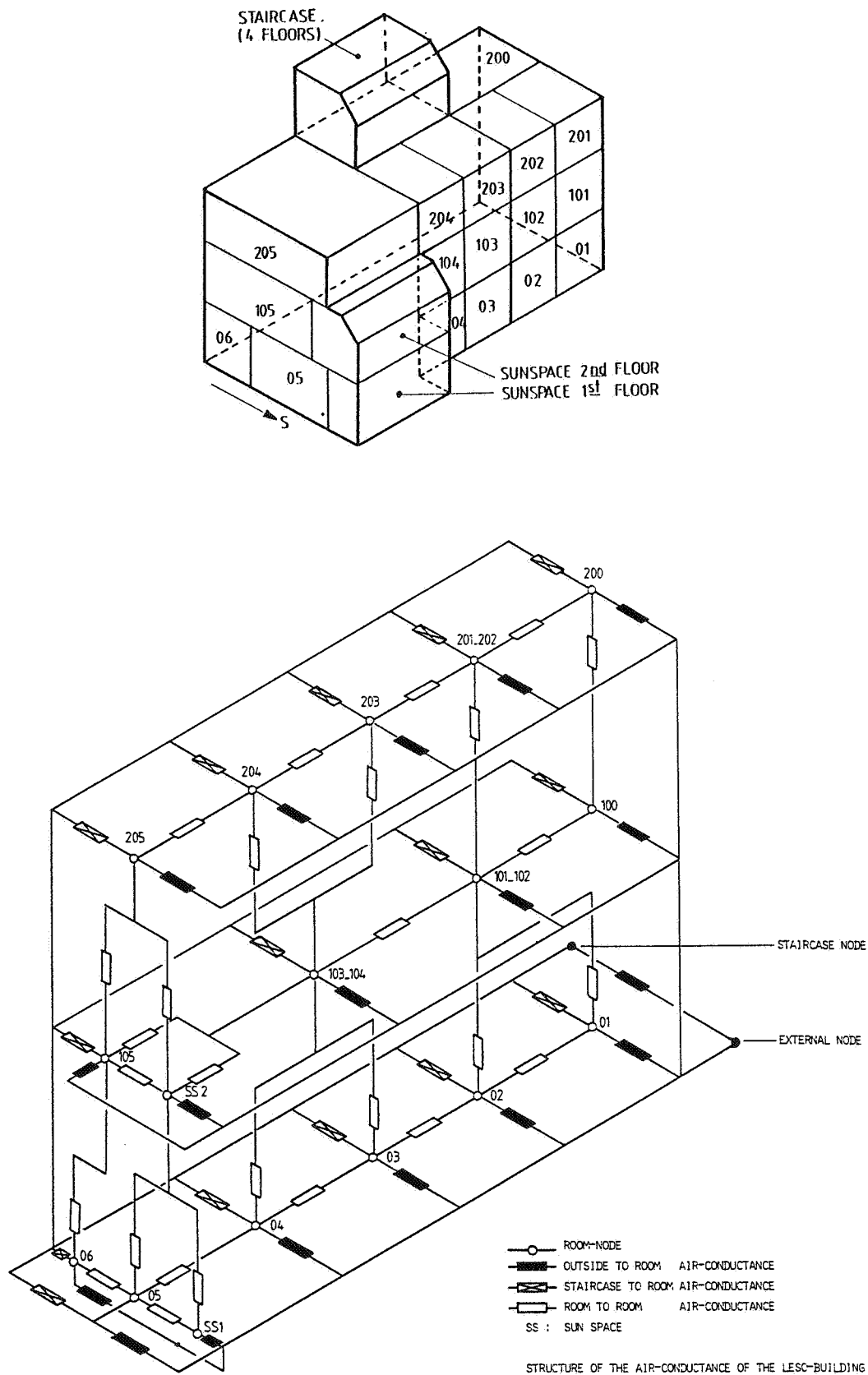


Fig. 7 : Flow paths interconnection and zones of the LESO building.

The permeability distribution of the building is determined by performing multizone pressurization tests. Attempts to measure these permeabilities with a single blower door by applying new strategies have failed [16]. Consequently, two blower doors are used to determine the unknown permeabilities of the building components.

Measurements of surface pressure coefficients on scale models have been performed in a boundary layer wind tunnel of the University of California to be able to calculate the wind pressure distribution around the building. This is an important input parameter for the infiltration model. The knowledge of the wind pressure distribution is especially necessary in order to compare the infiltration calculated by the model to that measured. Forty-four pressure probes have been installed in the vertical surfaces of the LESO model (shown in Figure 8). The surface pressure has been measured by using a single pressure transducer, which is connected with one of the pressure probes via a multiple valve. The building arrangement including the vicinity of LESO has been placed on a turntable to allow the measurement of surface pressure coefficients for different wind directions (see Figure 9). Therefore, for each 15 degree change of the wind directions, the multiple valve is scanned through the whole circle of pressure probes including the Pitot tube used to determine the pressure at the location of the LESO weather station.

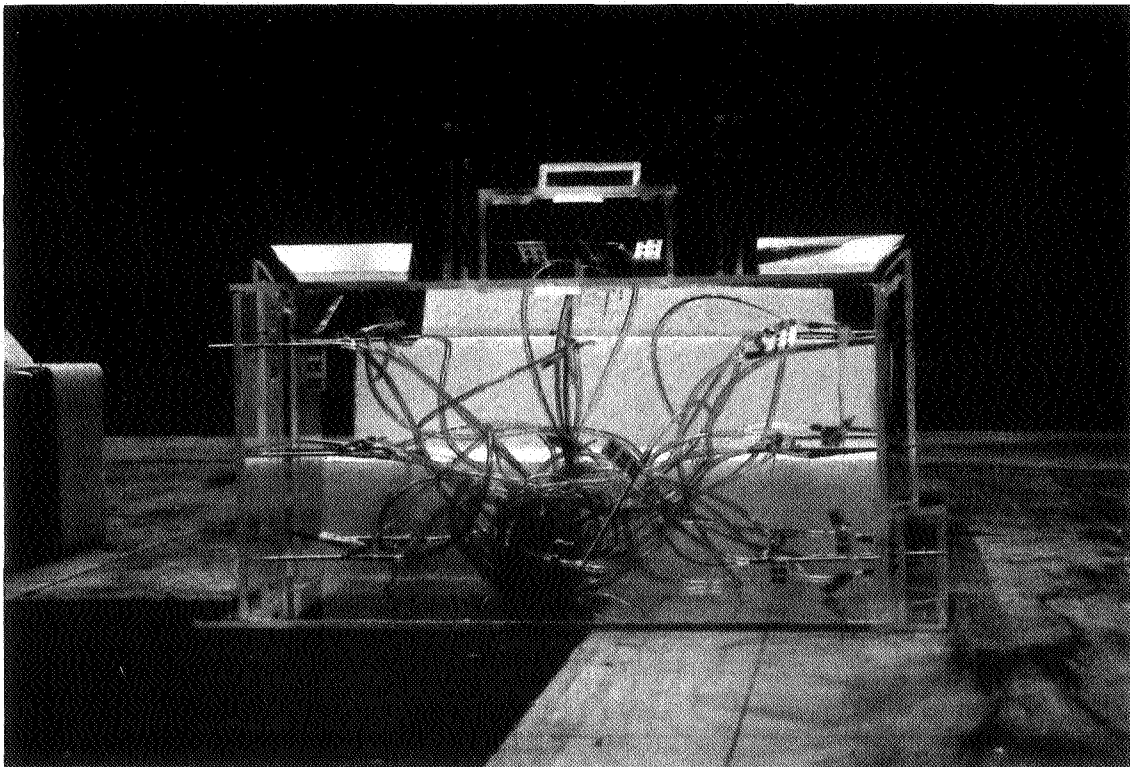


Fig. 8: Scale model of LESO

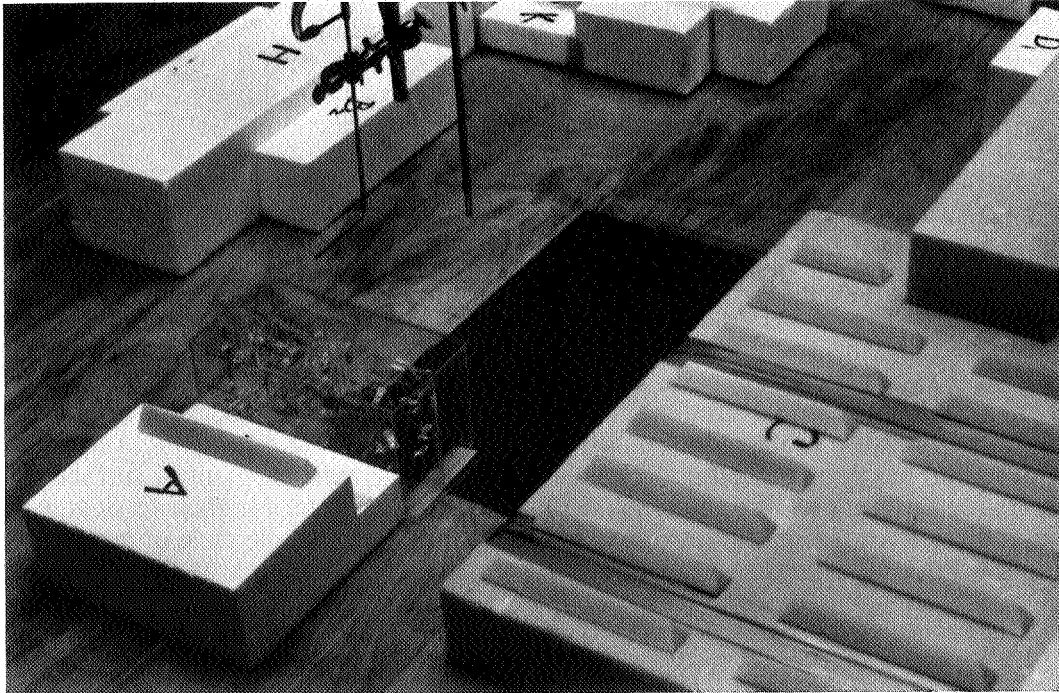


Fig. 9 : LESO and its surroundings

Monitoring the internal and external conditions is also made on the building site; this latter one is part of the instrumentation of the overall building containing over 450 channels. A list of quantities related to the air infiltration problem measured on the building is given in Figure 10.

On-site weather data are also used to calculate the wind pressure field around the building by employing the pressure coefficients evaluated during the wind tunnel experiments.

<u>Measured quantity</u>	<u>Number of probes</u>
Solar radiation	9
Outdoor air temperature	1
Wind speed and direction	2
Diff. pressure on south facades	6
Indoor air temperature	38

Fig. 10 : List of the monitored quantities related to air infiltration problem.

Empirical validation will be carried out by comparing the following physical quantities

- 1) Hourly values of outdoor to room air flowrates
- 2) Hourly values of interzonal flowrates

In order to compare the results of the simplified infiltration model with real building measurements, mutizone tracer gas measurements are performed by applying the constant concentration method with a single tracer gas to 10 zones of the building. Samples for each zone are taken and analyzed utilizing an infrared gas analyzer (CESAR apparatus[17]). By using different gas concentration strategies, instantaneous values of outdoor to room and interzonal flows can be measured. The measurements are performed for periods of one or two weeks.

Monitoring the weather conditions is done simultaneously to the tracer gas experiments. This procedure will be repeated for selected adequate periods, during which the building is not occupied (Christmas vacations).

6. CONCLUSIONS

The validity of air infiltration and ventilation models must be checked in order to increase the confidence in these programs. Experience gained from the huge research effort which has been conceded during the past decade to the validation of building thermal analysis models must be used. One of the main goals of this work has been the set-up of a satisfactory validation methodology which can be applied to validate the air infiltration model. On the other hand, more sophisticated air infiltration measurements techniques have been developed during the last years which should significantly help us to carry out this objective. Following this idea, validation of the simplified model developed at LBL will be undertaken : a joint research project, involving both EPFL and LBL collaboration has been set up for this purpose and has been exposed in this paper.

7. NOMENCLATURE TABLE

c	average pressure coefficient [-]
g	acceleration of gravity [m/s^2]
n	exponent of the pressure difference [-]
P_{dyn}	dynamic pressure of the undisturbed flow [Pa]
P_{in}	inside pressure [Pa]
P_{out}	outside pressure [Pa]
ΔP_{stack}	pressure difference due to stack [Pa]
ΔP_{wind}	pressure difference due to wind [Pa]
x, y, z	coordinates [m]
z_n	neutral pressure level [m]
D	air permeability of the building component [$m^3/h Pa^2$]

D_{res}	resultant permeability [m^3/h]
Q	air flow through a building component [m^3/h]
ρ_{out}	density of the outside air [kg/m^3]
ρ_{in}	density of the inside air [kg/m^3]
ϕ	wind direction [$^\circ$]

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PAPER 8

APPLICATIONS OF A SIMPLIFIED MODEL FOR PREDICTING
AIR FLOWS IN MULTIZONE STRUCTURES

TORE HAUGEN¹ AND HELMUT E. FEUSTEL²

¹Norwegian Institute of Technology
Trondheim-NTH
Norway

²Lawrence Berkeley Laboratory
Berkeley
CA 94720
USA

Abstract

A simplified pocket calculator model has been developed which can simulate the air flow distribution in multizone structures. The model is based on lumped parameters and includes several assumptions to simplify the description of air flow due to wind and stack effect and their superimposition. This paper gives a brief overview of the model and describes several applications. Results for simulation runs using the simplified model are compared with results obtained from a mainframe based research tool. The examples show that the simplified method can be used to predict air mass flows within reasonable accuracy for different types of buildings. We are able to calculate air flows due to wind or stack effect within a few percent difference from results calculated with a detailed model. We might expect larger differences when superimposing flows caused by different effects.

Table of Symbols

c_k	pressure coefficient for surface element k [-]
c_{lee}	pressure coefficient on leeward side [-]
c_{wind}	pressure coefficient on windward side [-]
dz	height gradient [m]
f_{in}	iteration damping factor [-]
g	acceleration of gravity [m/s^2]
h	height of the building [m]
j	number of considered story [-]
i	iteration step [-]
k	number of stories [-]
lee	leeward side
luv	windward side
n	exponent of the pressure difference [-]
p	pressure [Pa]
p_0	atmospheric pressure [Pa]
p_{dyn}	dynamic pressure in the undisturbed flow [Pa]
p_{in}	inside pressure [Pa]
p_k	pressure at surface element k [Pa]

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p_{out}	outside pressure [Pa]
Δp_{stack}	pressure difference due to stack [Pa]
Δp_{tot}	pressure difference due to stack and wind action [Pa]
Δp_{wind}	pressure difference due to wind [Pa]
$sign$	sign of the following expression [-]
$t_{in}; t_{out}$	temperature inside; outside [$^{\circ}$ C]
v	wind speed [m/s]
x, y, z	coordinates [m]
z_n	neutral pressure level [m]
z_0	reference height for wind velocity measurements [m]
D	air permeability of the building component [$m^3/h Pa^n$]
D_{lee}	air permeability of the leeward side of the building envelope [$m^3/h Pa^n$]
D_{res}	resultant permeability [$m^3/h Pa^n$]
D_{shaft}	air permeability from the story to the shaft [$m^3/h Pa^n$]
D_{total}	air permeability of the total building envelope [$m^3/h Pa^n$]
Q	air flow through a building component [m^3/h]
Q_{tot}	superimposition of flows [m^3/h]
Q_{wind}	air flow due to wind [m^3/h]
Q_{stack}	air flow due to temperature differences [m^3/h]
$T_{in}; T_{out}$	temperature inside; outside [K]
α	exponent [-]; value depends on terrain roughness
ϕ	wind direction [$^{\circ}$]
ρ_{out}	density of the outside air [kg/m^3]
ρ_{in}	density of the inside air [kg/m^3]

1. INTRODUCTION

Awareness of the air flow pattern in a building is particularly important when determining indoor air quality problems for the different zones in a building, smoke distribution during a fire, and space conditioning loads for calculating energy consumption. The correct sizing of necessary space conditioning equipment is also dependent upon accurate air flow information.

Infiltration is the pressure driven, uncontrolled flow of air through openings in the building envelope. Pressure differences are caused either by wind action, stack action or mechanical ventilation systems. Wind flows produce a pressure field around the building. Pressure differences between different location of the building envelope force air flows inside the structure. Temperature differences between the outside and inside of a building create air density differences that cause pressure gradients. Buoyancy forces try to eliminate these differences, causing a vertical stream of air inside the building depending.

A number of computer programs have been developed to calculate infiltration-related energy losses and the resultant air flow distribution in buildings [1]. Mainframe computers are the standard hardware used to host models designed to solve the set of nonlinear equations created by air flow patterns through building components. If the true complexity of air flows brought about by climatic variables is to be properly treated in multizone buildings, extensive information regarding flow characteristics and pressure distribution inside and outside the building is essential. To reduce the necessary input data required by detailed infiltration models, researchers have developed a variety of simplified models. Most of these models, including the one developed at the Lawrence Berkeley Laboratory [2], simulate infiltration associated with single-cell structures. (Air flow in a building that can be described as one fully-mixed space without any internal flow restrictions and no pressure gradients in the horizontal direction can also be calculated by using single-cell infiltration models.)

A high percentage of existing buildings, however, have floor plans that characterize them more accurately as multizone structures. Detailed infiltration models usually describe buildings as an interlaced grid of flow paths. In this system, the joints are the zones of the building, and the connections between the joints simulate the flow paths. The grid points outside the building mark the boundary conditions for wind pressure.

The duct system in buildings with mechanical ventilation systems, can be treated as another interior flow path, the fan being an additional source of pressure difference. The fan increases the pressure level between two joints according to the characteristic curve of the fan.

Due to the nonlinear dependency of the flow on the pressure difference, the pressure distribution is generally calculated in several iterations. For detailed multizone infiltration models describing buildings with complicated floor plans and solving the resulting set of nonlinear equations, a computer with a large storage capacity is needed. Although multizone models exist, the vast majority are 1) not readily available to the end user and 2) written as research tools requiring inordinate amounts of input data to describe the external pressure distribution and air permeability distribution of the building [1]. Furthermore, to determine the impact of infiltration and air flow patterns within buildings, engineers and architects need a simplified multizone infiltration model.

Therefore, LBL has developed a simplified model, categorizing buildings on the basis of their ratio of air permeability [3]. In this paper, applications of such a model are shown. Results for simulation runs using the simplified model are compared with results obtained from a mainframe based research tool.

Table 1: Comparison of modeling strategies		
Model	Advantage	Disadvantage
single-cell	easy to handle, requires few input data, provides reasonable accuracy	simulates only single cell structures; i.e., no internal flows or partitions
detailed	useful for larger buildings, measures internal flows, has good accuracy	requires extensive input and mainframe computer
simplified multizone	very useful for larger buildings, measures internal flows, is easy to use, requires reduced input, can be calculated on pocket calculator	reduced accuracy

2. SIMPLIFICATION

2.1 Overview

To simplify the calculation procedure, we adopted the following measures:

- 1) define a set of lumped parameters to describe the permeability distribution of the building
- 2) use a single exponent for the pressure distribution
- 3) use an average air density to calculate the infiltrating and exfiltrating air flows
- 4) calculate the wind- and stack-driven air flows separately
- 5) use superimposition to combine the air flows.

2.2 Resultant Permeability

The pressure drop along the crack length can be expressed in terms of friction and resistances. The air flow through building components is usually described by the empirical power-law equation

$$Q = D (p_1 - p_2)^n \quad (1)$$

A buildings effective air permeability for infiltration is often a combination of air permeabilities arranged in series and/or in parallel. For permeabilities having the same flow exponent, parallel permeabilities can be easily added, whereas those in a series arrangement have to be calculated as follows:

$$Q = D_{res} \left\{ (p_1 - p_2) + (p_2 - p_3) + \dots + (p_{k-1} - p_k) \right\}^n \quad (2)$$

$$Q = D_1 (p_1 - p_2)^n = D_2 (p_2 - p_3)^n = D_{k-1} (p_{k-1} - p_k)^n \quad (3)$$

$$D_{res} = \left\{ D_1^{-1/n} + D_2^{-1/n} + \dots + D_{k-1}^{-1/n} \right\}^{-n} \quad (4)$$

Figure 1 illustrates resultant air permeability for two resistances in a series arrangement with exponent $n=2/3$.

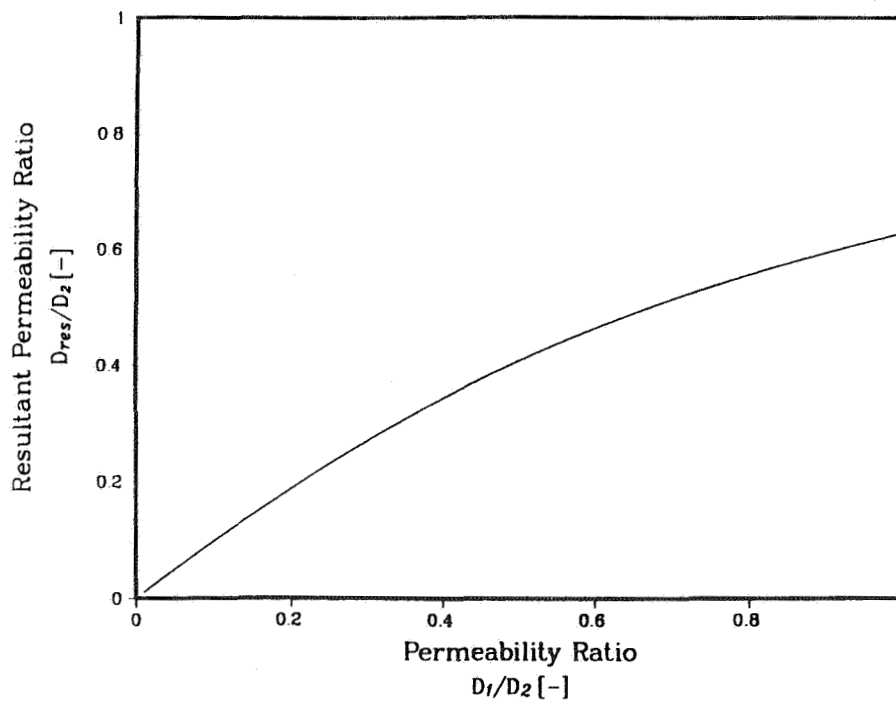


Fig. 1: Resultant permeability ratio versus permeability ratio

2.3 Superimposition of Flows

Air flows caused by separate mechanisms (such as wind and thermal buoyancy) are not additive because the flow rates are not linearly proportional to the pressure differences. To calculate the flows, superimposing the pressures is required.

$$Q_{tot} = D (\Delta p_{tot})^n \quad (5)$$

$$Q_{tot} \approx D (\Delta p_{wind, horizontal} + \Delta p_{wind, vertical} + \Delta p_{stack})^n \quad (6)$$

$$Q_{tot} \approx (Q_{wind,horizontal}^{1/n} + Q_{wind,vertical}^{1/n} + Q_{stack}^{1/n})^n \quad (7)$$

Because each mechanism may force the air to flow in a different direction, the superimposition of flows for each facade and story is expressed as:

$$Q_{tot} = \text{sign}(Q_{wind,horizontal} + Q_{wind,vertical} + Q_{stack}) \times$$

$$\left| \left[\text{sign}(Q_{wind,horizontal}) |Q_{wind,horizontal}|^{1/n} + \right.$$

$$\left. \text{sign}(Q_{wind,vertical}) |Q_{wind,vertical}|^{1/n} + \right.$$

$$\left. \text{sign}(Q_{stack}) |Q_{stack}|^{1/n} \right| ^n \quad (8)$$

Figure 2.1 and 2.2 show that both driving forces for natural ventilation can be calculated separately and superimposed to obtain the total natural ventilation.

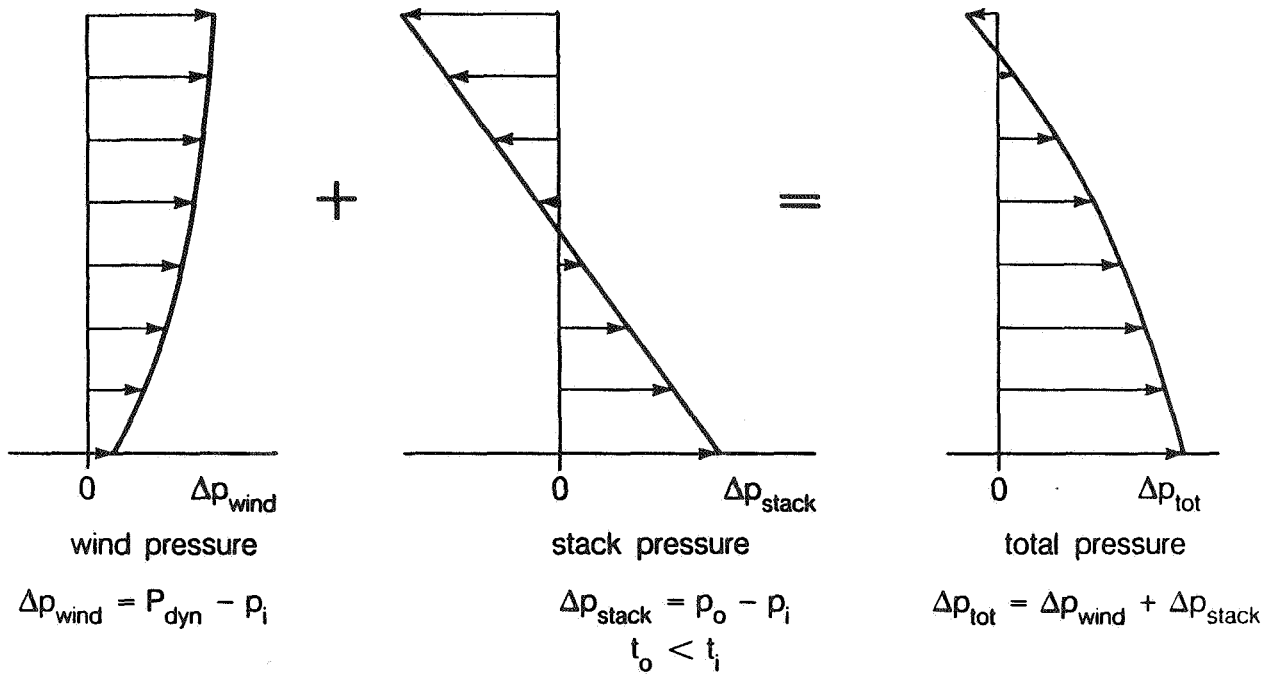


Fig. 2.1: Superposition of pressures for the windward side

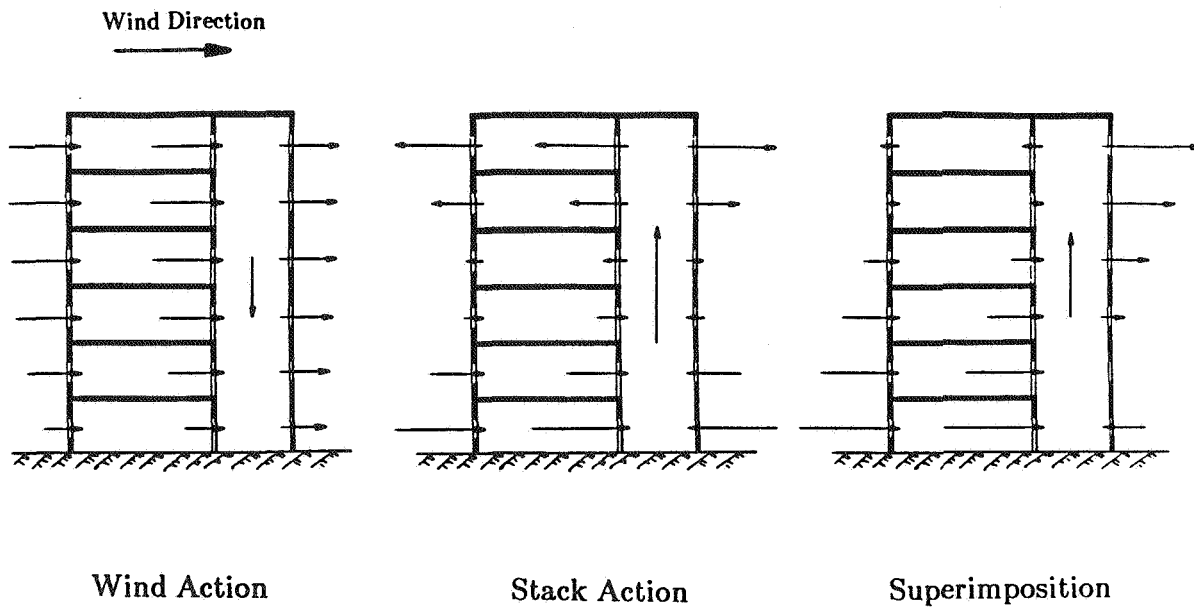


Fig. 2.2: Air flow pattern in multi-story building

2.4 Lumped Parameters

Several lumped parameters reflecting the different permeability distributions of the building's envelope have been found to describe the air flow distribution inside a building [3]. Krischer and Beck [4] used the following parameter to describe the envelope permeability ratio (*epr*) of the whole building:

$$epr(\phi) = \frac{D_{lee, envelope}}{D_{total, envelope}} \quad (9)$$

The influence of the envelope permeability ratio on the resultant permeability of a structure and its infiltration is shown in Fig. 3. Due to the fact that the value of the resultant permeability is governed by the smallest permeability in a series arrangement, the infiltration rate for a given permeability of the total envelope reaches its maximum at an envelope permeability ratio of 0.5 (typical row house). Therefore, for buildings with the same overall leakage, but an uneven distribution of the air permeabilities between the leeward and the windward side, the infiltration will be smaller. The wind-driven infiltration under steady-state conditions will be zero if all air permeability is located on either side.

Another parameter to further differentiate construction types was obtained from the German standard for calculating heat loss in buildings, DIN 4701 [5]. Based on this parameter we introduced the ratio of the permeabilities from one floor to another, and the overall permeability of the building envelope. Equation 10 describes the vertical permeability ratio (*vpr*) for a whole building of any given construction type.

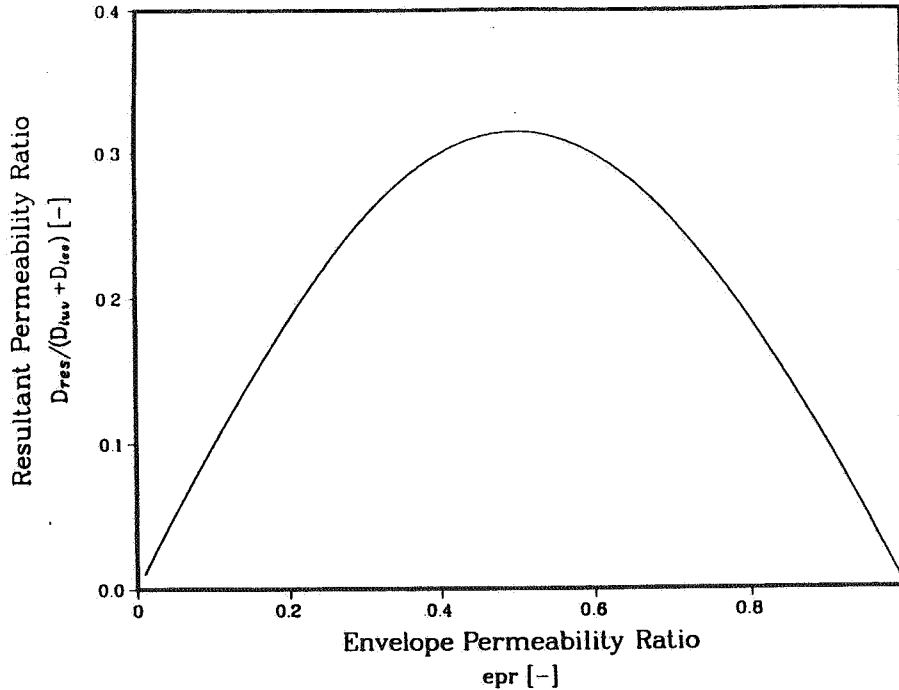


Fig. 3: Resultant permeability ratio versus envelope permeability ratio

$$vpr = \frac{D_{shaft}}{D_{total, envelope} + D_{shaft}} \quad (10)$$

With regard to thermal pressure distribution, two extremes exist — *story-type buildings* with no permeability between floors ($vpr = 0$), and *shaft-type buildings* with no air-flow resistance between the different stories ($vpr = 1$). The vertical permeability ratio for real houses is somewhere between these theoretical limits.

To describe the air-flow distribution for the different zones at the story level, we defined two additional lumped parameters. It was determined [3], that the internal air flows due to wind at the story level are directly dependent upon the ratios of the resultant permeabilities of the different zones. These are defined as the combination of all flow paths (parallel and series arrangements) from this zone to either the windward or leeward side of the building. The resultant permeability ratio (rpr) is the ratio of the resultant permeability of the downstream side to all resultant permeabilities of this particular zone. The permeability ratio contains all information given by the outside permeability ratio together with all the flow paths not directly leading to the outside of the building.

$$rpr(\phi) = \frac{D_{res, zone, lee}}{D_{res, zone, total}} \quad (11)$$

The majority of the permeabilities have to be shared by different flow paths. Calculating the resulting permeability ratio for the internal flows may require an iteration procedure. To determine the initial value for the iteration process the outside permeability ratio (opr) of the zone can be used. It describes the cross-ventilation of the zone, where cross-ventilation is the portion of the total air flow that exfiltrates the same zone it infiltrates.

Therefore, no permeabilities between internal zones have to be taken into consideration.

$$opr(\phi) = \frac{D_{zone, lee, outside\ envelope}}{D_{zone, outside\ envelope}} \quad (12)$$

2.5 Air Flow Compensation

Besides the determination of the permeability distribution and the pressure field around the building, the most difficult aspect of calculating wind-driven infiltration is the determination of the inside pressure distribution of the building. Different wind speeds in different heights also cause air flows through the shafts of a building. Majority of the time air flows due to stack action travel upwards ($t_{in} > t_{out}$), but wind forces an air flow from the top to the bottom of the building.

Because the air-flow through the shaft due to wind action and thermal buoyancy causes no significant friction loss in the shaft, it can be assumed to have no pressure gradient inside the shaft itself.

$$0 = \sum_{j=1}^k \left\{ p_{in,j} - p_{shaft} \right\}^n \approx \sum_{j=1}^k \left\{ p_{in,j} - p_{shaft} \right\} \quad (13)$$

$$p_{shaft} = \frac{1}{k} \sum_{j=1}^k p_{in,j} \quad (14)$$

For this calculation, the inside pressures of story-type buildings may be used. The high pressures at the top of the building cause a downstream of infiltrated air in the shaft. This air is released into the lower levels of the building. This has a most significant effect for the flow distribution in houses having small *epr*-values.

For buildings having a flow resistance between the shaft and the floor landing, the following empirical equation gives the approximate value for the pressure of the landing as a function of the building's height above ground and the building type [6].

$$p_{in}(z, epr, 0 < vpr < 1) = p_{shaft} + \frac{\left\{ p_{in}(z=h, epr, vpr=0) - p_{shaft} \right\}}{h/2} (1 - vpr^n) (z - h/2) \quad (15)$$

For shaft type buildings the pressure of the landing becomes the shaft pressure itself.

3. CALCULATION PROCEDURE

3.1 Air Flows sharing Air Permeabilities

The portion of air permeability used by different flow paths can be determined by splitting the single permeability by the same ratio as the parallel permeabilities belonging to these flow paths. A single permeability on the windward side of the building, which is used by flow paths through two different permeabilities on the leeward side can be calculated as follows:

$$D_{wind,1} = D_{wind,total} \frac{D_{res,lee,1}}{D_{res,lee,1} + D_{res,lee,2}} \quad (16)$$

The combination of permeabilities are, for the most part, not as simple as the above example. The resultant air permeability of a flow path may be a combination of series and parallel arrangements passing through a series of different zones. Therefore, the resultant permeabilities of the leeward side ($D_{res\ lee,1}; D_{res\ lee,2}$) might not be determined yet. The share of the windward side permeability related to $D_{res\ lee,k,l}$ can be calculated by taking the leeward permeabilities of the considered zone and the rpr -differences into account.

$$D_{wind,k,l} = D_{wind,total} \frac{(rpr_k - rpr_l) D_{lee,k,l}}{\sum_{j=1}^n [(rpr_j - rpr_l) D_{lee,j,l}]} \quad (17)$$

The value of the resultant permeability ratio for the windward side of the building is defined as $rpr = 0.0$ whereas the value for the leeward side becomes $rpr = 1.0$. Using these values, resultant permeability ratio differences between inside and outside can be calculated. The calculation becomes more time consuming if the air flow direction of one or more flow paths is different from that assumed by using the opr -values. In this case, part of the leeward flow path is not yet determined as it goes through different zones. Consequently, the portion of this additional leeward flow path is generally quite small compared to the direct flow through the zone. In most cases it is negligible. The main reason for the wrong initial direction on this particular flow is missing information on internal flow paths at the starting point. Usually, this occurs only in zones with opr -values lower than 0.5. The calculation procedure indicates the wrong flow direction normally after one or two iteration steps by producing negative results for some of the rpr -differences.

In order to prevent the iteration procedure from diverging, the newly calculated values should be accepted with caution. For further calculations, these values should be weighted by a factor which expresses the uncertainty of the results of the determined iteration step. Several tests have shown that

$$f_{in} = \frac{i}{i + 1} \quad (18)$$

where the iteration step i , is a reasonable damping factor.

3.2 Pressure Distribution

Wind pressure is one of two main driving forces for natural ventilation. The pressure distribution around a building is usually described by dimensionless pressure coefficients -- the ratio of the surface pressure and the dynamic pressure in the undisturbed flow pattern:

$$c_k(x, y, z, \phi) = \frac{p_k(x, y, z) - p_0(z)}{p_{dyn}(z)} \quad (19)$$

with

$$p_{dyn}(z) = \frac{1}{2} \rho_{out} v^2(z) \quad (20)$$

The vertical profile of the wind speed in the atmospheric boundary layer is primarily dependent upon the roughness of the surface surrounding the building. The wind speed increases with the increasing height above ground. The wind velocity profile can be calculated by a power law expression.

$$\frac{v(z)}{v(z_0)} = \left\{ \frac{z}{z_0} \right\}^\alpha \quad (21)$$

Temperature differences between the outside and inside air create air density differences that cause pressure gradients. The stack-effect pressure gradient depends only upon temperature differences and the vertical dimension of the structure. The effect deals with the weight difference of the two adjacent columns of air. Buoyancy forces try to even out these differences, causing an overpressure at the top of the warm column of air, and an underpressure at the bottom. The value of pressure differences in high rise buildings located in cold climates can easily exceed those caused by wind effects. The theoretical value of the pressure difference depends on the gradient and distance of the neutral pressure level (z_n). This is defined as the height on the building facade where, under calm conditions, no pressure difference exists between inside and outside. The vertical permeability distribution of the envelope determines the location of the z_n . For only one opening or for an extremely large opening relative to others, the neutral pressure level is at or near the center of the opening. For openings uniformly distributed vertically, the neutral pressure level is at almost midheight of the enclosure. Locating the neutral pressure level for simple enclosures with openings of known air flow characteristics are rather straightforward. For two openings separated by a known vertical height H , it can be found by the equation [7]

$$z_n = \frac{H}{1 + [(A_1/A_2)^2 (T_{in}/T_{out})]} \quad (22)$$

The stack effect (or thermal buoyancy) can be calculated by

$$(p_{in} - p_{out})_{stack} = g (\rho_{out} - \rho_{in}) (z - z_n). \quad (23)$$

3.3 Calculating Air Flows

Air flows due to the different effects have to be calculated separately. Wind induced flows can be calculated by multiplying each resultant permeability with the pressure difference between the windward and leeward side at a given height to the power of n.

$$Q_{wind,1} = D_{res,wind,1} [p(z)_{windward,1} - p(z)_{leeward,1}]^n \quad (24)$$

Flows caused by stack effect and the vertical flow in shaft type buildings can be calculated by multiplying the resultant permeability between the shaft and the outside of a building by the pressure difference between the shaft and the outside at the considered level above ground to the power of n.

$$Q_{stack,1} = D_{res,stack,1} |p(z)_{shaft} - p(z)_{out}|^n \quad (25)$$

4. USE OF THE SIMPLIFIED MODEL

4.1 General

In this section is shown the use and the accuracy of the simplified model. This model calculates the air flows for each zone in different buildings ranging from a single family building, to multistory apartment buildings. The model has been tested for different distribution of permeabilities, different outdoor temperatures, wind speeds and wind directions. All calculations with the simplified model are compared for accuracy with the results from a detailed multizone model [1,6] using the same kind of input for the permeabilities and weather conditions. The simplified model can be used with only a pocket calculator. Our first example is intended to illustrate a way for users not yet familiar with this method.

4.2 Boundary Conditions

The boundary conditions used in all examples and for calculations with both the simplified and the detailed mathematical model are given below:

outdoor temperature (t_{out})	+5 °C and -10 °C
inside temperature (t_{in})	20 °C
height of stories	3 m
wind speed at reference height (v_o)	4 and 8 m/s
wind direction perpendicular to windward side	
reference height for wind speed measurements (z_o)	10 m

exponent for vertical wind profile (α)	1/3 *
exponent for pressure differences (n)	2/3
pressure coefficient windward side (c_{wind})	1.
pressure coefficient leeward side (c_{lee})	-0.3
air permeability of building components (D)	(see floor plans)

4.3 Example of a Calculation Procedure

The calculation procedure for a simple floor plan has been shown in a previous paper [6]. In order to get a complete overview of the use of the model, all the necessary steps for a calculation of a more complex building will be shown here. The building (Brunsbuettler Damm, Berlin) was built in 1965. An open staircase connects the 8 stories, containing 3 flats per floor. One of the flats has only windows to one side of the building. The main facade with the open stair (exterior wall as part of staircase) faces east.

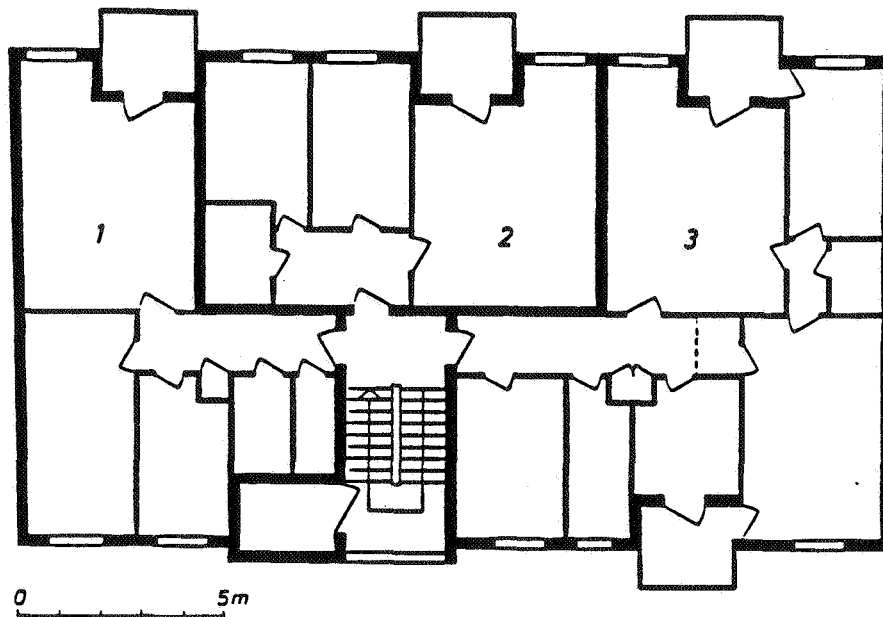


Fig. 4: Floor plan Brunsbuettler Damm 37

* For details on wind profile see [4].

4.3.1 Infiltration - different zones

The calculation of the infiltration for different zones is more intricate, and will be shown step by step. The different permeabilities are shown in Fig. 5.1. As the flow paths and flow directions could be different for infiltration caused by wind and stack effect, one will have to calculate these flows separately and then superimpose them according to Equation 7 to get the final result.

Table 4.1: Calculation Procedure Iteration step: Initial

DESCRIPTION	#	FLAT # 1	FLAT # 2	FLAT # 3	STAIR (#4)
D_{stair}	1	---	---	---	---
D_{door}	2	18.	18.	18.	---
$D_{res:\#1,\#2}$	3	---	---	---	---
D_{wind}	4	4.3	---	19.6	20.
D_{lee}	5	8.6	11.6	17.1	---
$D_{lee, stair}$	6	---	---	---	---
$D_{res:\#2,\#6}$	7	---	---	---	---
$D_{res:\#3,\#6}$	8	---	---	---	---
$D_{res:\#4,(\#5-\#6)}$	9	---	---	---	---
opr $\frac{\#5}{\#3+\#4+\#5}$	10	.667	1.000	.466	0.000
opr-difference	11	.667	1.000	.466	---
share of D_{stair}	12	6.3	9.4	4.4	---

Iteration step : #1

DESCRIPTION	#	FLAT # 1	FLAT # 2	FLAT # 3	STAIR (#4)
D_{stair}	1	6.3	9.4	4.4	---
D_{door}	2	18.	18.	18.	---
$D_{res:\#1,\#2}$	3	5.52	7.58	4.05	---
D_{wind}	4	4.3	---	19.6	20.
D_{lee}	5	8.6	11.6	17.1	8.
$D_{lee, stair}$	6	4.83	11.6	2.93	---
$D_{res:\#2,\#6}$	7	4.43	8.79	2.81	---
$D_{res:\#3,\#6}$	8	---	---	---	---
$D_{res:\#4,(\#5-\#6)}$	9	---	---	---	---
rpr $\frac{\#5}{\#3+\#4+\#5}$	10	0.55	0.75	0.44	0.29
rpr-difference	11	0.26	0.46	0.15	---
share of D_{stair}	12	6.0	10.6	3.5	---

Windeflect - story type building

Considering the building first as a story type building with no connection between the different floors ($vpr=0.0$). The first step is to find the flow paths for each story, keeping in mind, that air flows from zones with low rpr-values to those with high rpr-values.

The flow paths for the given building using opr -values as initial values for the resultant permeability ratio are illustrated in Fig. 5.1. The opr -values are 0.667 for flat 1, 1.0 for flat 2, 0.446 for flat 3 and 0.0 for the staircase (number 4). This is the initial step; for each next iteration step one will have to follow the procedure below. The calculated values are weighted by a iteration factor f_{in} , which expresses the uncertainty of the the result of the determined iteration step (Equation 18).

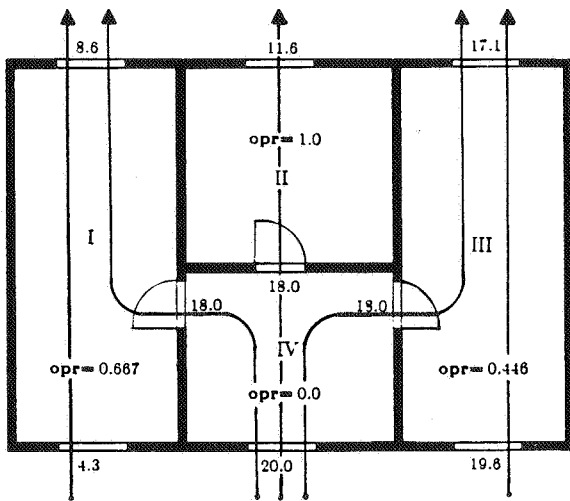


Fig. 5.1: Initial step - Assumed flow paths

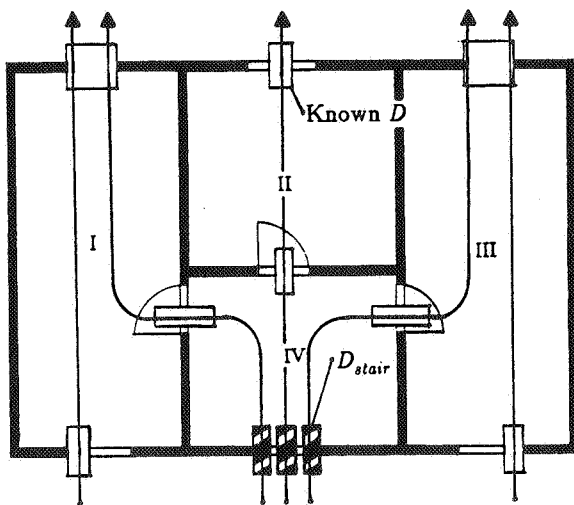


Fig. 5.2: Step #1 - Finding D_{stair}

The numbers given in the following description relate to the steps in Table 4.1 and Figs. 5.2 - 5.5.

1. D_{stair} for each flat is given as the share of the windward permeability in the staircase.
2. Initial value; no changes.
3. D_{res} as the resultant of D_{stair} and D_{door} for each flat. This value can be found by using the table of resultant permeabilities for two permeabilities in a series arrangement (Appendix I).
4. Initial value; no changes.
5. Initial values; except for D_{lee} staircase, which equals the sum of $D_{res:\#2,\#6}$ for flat 1, 2 and 3 multiplied with the damping factor f_{in} (here 0.5 for $i=1$).
6. $D_{lee, stair}$ is the share of the flat's leeward permeability D_{lee} belonging to the flow path including D_{res} . It is found by splitting the permeability by the same ratio as the parallel permeabilities (Equation 16).
7. $D_{res:\#2,\#6}$ is the resultant permeability of the leeward flow path of the staircase.
8. $D_{res:\#3,\#6}$ is the resultant permeability of the flow path through the staircase to leeward side of the flat. These are only necessary at the last iteration step for calculation of the

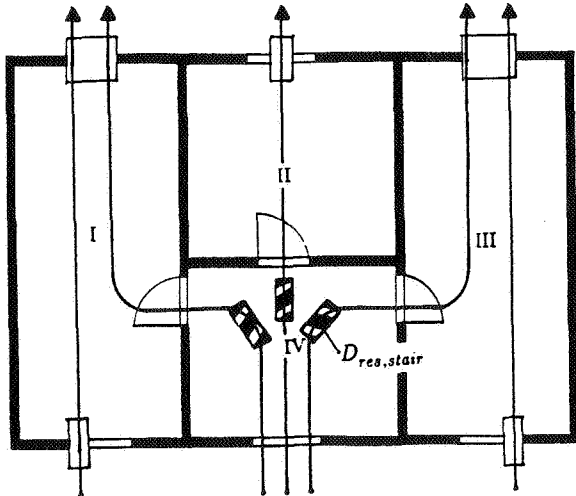


Fig. 5.3: Step #3 - Finding D_{res} for D_{stair} and D_{door}

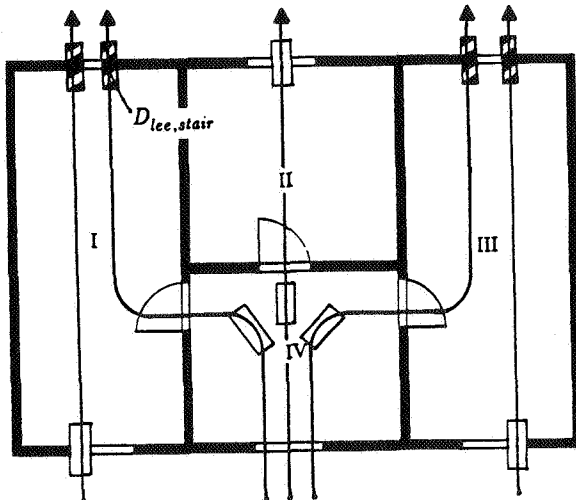


Fig. 5.4: Step #6 - Splitting D_{lee} to find $D_{lee, stair}$

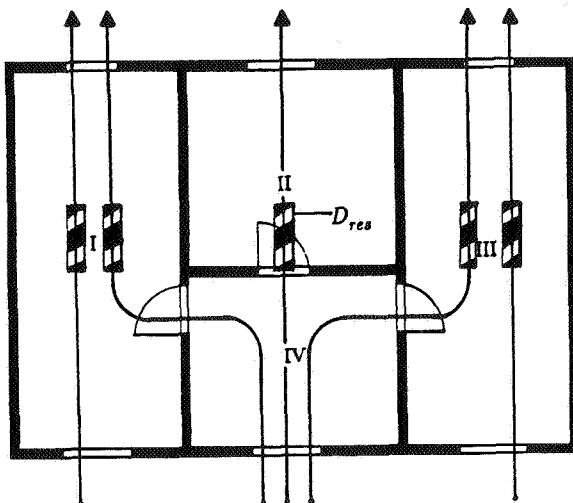


Fig. 5.5: Step #8, #9 - Finding D_{res} for all flows

air flow, and are therefore not calculated at each iteration.

9. $D_{res: \#4, (\#5-\#6)}$ is the resultant permeability of the through flow from the windward to the leeward side of the flat. These are also only necessary to find at the final iteration.

10. New rpr -values are calculated in order to continue with the next iteration step. D_{res} values are always multiplied by the iteration factor f_{in} .

11. Rpr -differences are the differences between rpr -values for the stair and the flats. They are used to find D_{stair} for the next iteration step.

12. Share of D_{stair} is found by dividing D_{wind} for the stair by the sum of rpr -differences from step 11, and multiply by the rpr -difference for the flat. This value will also be the value for D_{stair} (#1) in the next iteration step.

The detailed result for the second and third iteration step is shown in Appendix II. The differences in the air mass flow for the different flow paths are very small for this building. The only exception is the flow through the door of flat 3. But even if the mass flow for this path changes about 50% with 5 iteration steps, the change of the total flow for the flat 3 is only 2.5%.

Therefore, if the total air flow per zone is more important than the air flow for a particular flow path, the first iteration step gives a reasonable result. If, however, the values for a particular flow path is important, the number of iteration steps is determined by the smallest rpr -difference between zones.

Wind effect - shaft type building

The pressure in the shaft due to wind is dependent on the wind pressure profile, which causes high pressures in the upper flats and low pressures in the lower flats. The high pressures at the top of the building cause a downstream of infiltrated air in the shaft. This air is released into the the lower levels of the building, so that the pressure differences between the staircase and the flats becomes very small and even negative. Because of no significant friction loss in the shaft, it can be assumed, to have no pressure gradient inside the shaft itself. We can determine the shaft pressure by averaging the pressure in the staircase for the story type building (Equation 14).

Stack effect - shaft type building

The difference in thermal pressures for a given temperature difference under calm conditions is a linear function of the distance of the height above ground from the neutral pressure level (Equation 22).

$D_{res}(z)$ is the resultant permeability calculated for the arrangement of permeabilities in series or parallel between the zone where the stack pressure occurs (here the stair shaft) and the outdoor.

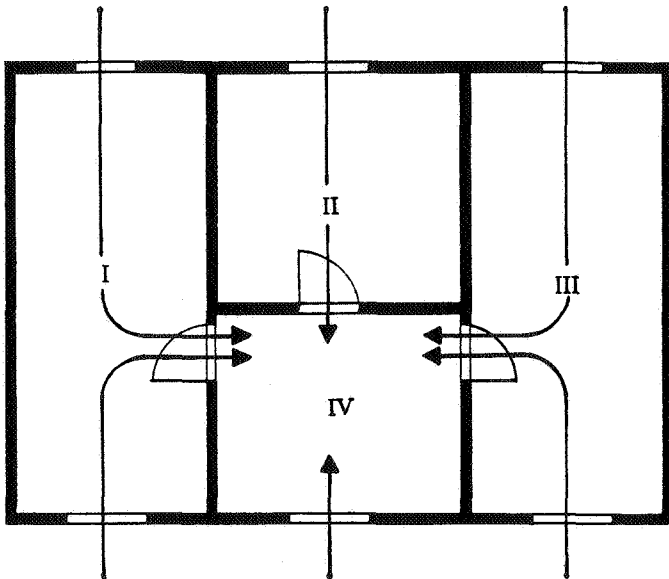


Fig. 5.6: Flowpaths below n_z due to stackeffect

Figure 5.6 shows the flow paths and the permeabilities for the first floor (will be opposite for floors above z_n). The resultant permeabilities again can be found using the table for two permeabilities in a series arrangement (Appendix I).

4.3.2 Resulting air flows

The air flows due to different effects are calculated separately using Eq. 24 and 25 with $n = 2/3$. Table 4.2 shows air mass flows calculated with the simplified model for the following cases: *wind effect - story type building; wind effect shaft type building; stack effect; stack- and wind effect* for the first floor in a shaft type building. The detailed model has been used to calculate the mass flows for the same effects.

Table 4.2: Air mass flows for the 1th floor [kg/h], 5 iteration steps, $v_n = 4 \text{ m/s}$, $t_{out} = -10 \text{ }^\circ\text{C}$, Wind perpendicular to facade							
model / case	Flat 1			Flat 2	Flat 3		
	wind	lee	door	door	wind	lee	door
<i>Simplified:</i>							
wind (story)	18.4	-40.5	22.1	44.5	76.2	-86.7	10.4
wind (shaft)	16.9	-43.3	28.6	48.9	73.4	-89.1	25.9
stack	23.9	47.9	-71.8	-67.9	61.0	53.3	-114.2
stack + wind	32.7	13.0	-59.3	-36.4	107.0	-58.8	-106.5
<i>Detailed:</i>							
wind (story)	18.5	-40.2	21.8	44.6	76.4	-85.2	8.8
wind (shaft)	16.4	-43.3	26.9	48.9	69.5	-89.5	20.3
stack	24.1	48.3	-72.4	-68.0	58.2	50.8	-109.0
stack + wind	35.1	14.6	-49.7	-32.8	126.9	-41.7	-85.2

The results of the simplified model are very close to those of the detailed model for flows caused by a single effect. Differences for flows caused by either wind or stack effect are in absolute values only a few percent. For the flow through the door in flat 3 the difference 18% for the *wind(story)* case, mainly because of its low absolute value.

The major differences appear for a situation with flows caused by both wind- and stack effect. The differences are up to 20% for flows through flat 1 (case: stack + wind), and up to 40% for flat 3. This is, if we express the differences as percent of a single flow. If we express the difference between the two methods as the difference for a single flow path in relation to the total airflow through one zone, the maximum difference for flows through flat 3 is 16.8%. As this is a more correct way of expressing the percentages for situation with very low air mass flows, this calculation procedure will be used in the following. To get reasonable results for the total mass flow through a zone and to find correct flow directions is very important.

Table 4.2 also shows that the superposition changes the mass balance for the zone. For each zone the sum of mass flows should by definition equal zero; as is the case for both wind and stack effect separately. After superimposing the flows, the mass flow balances are either positive or negative. This is due to the simplification procedure.

We have tried another approach, where we only superimpose two of the flows (here flow through windward and leeward side) through a zone with 3 different flows, and then in the finale step find the third mass flow from a mass flow balance of zero. But overall results are not better.

4.3.3 Changing outdoor temperature any wind speed

A building might be more or less dependent on either wind or stack effect. Table 4.3 shows the differences between the two methods for both wind and stack effect with varying outdoor temperature and wind speed.

Table 4.3: Air mass flows for the 1th floor [kg/h], Variable temperature and wind speed, Wind perpendicular to facade, Stack + wind effect, 5th iteration step							
v_o t_{out}	Flat 1			Flat 2	Flat 3		
	wind	lee	door	door	wind	lee	door
<i>Simplified:</i>							
4 m/s, +5 °C	24.2	-21.3	-28.6	11.7	85.8	-68.8	-60.1
4 m/s, -10 °C	32.7	13.0	-59.3	-36.4	107.0	-58.8	-106.5
8 m/s, +5 °C	45.5	-91.1	40.8	97.7	184.1	-200.8	-23.1
8 m/s, -10 °C	54.0	-86.9	2.0	86.8	207.9	-206.8	-78.7
<i>Detailed:</i>							
4 m/s, +5 °C	26.3	-17.1	-9.21	15.8	99.7	-57.0	-42.7
4 m/s, -10 °C	35.1	14.6	-49.7	-32.8	126.9	-41.7	-85.2
8 m/s, +5 °C	46.2	-91.2	45.0	100.0	192.8	-195.0	2.2
8 m/s, -10 °C	55.9	-85.9	30.0	91.6	230.0	-190.2	-39.8
<i>Difference %</i>							
4 m/s, +5 °C	-8.0	16.0	73.7	-26.0	-14.0	11.8	17.4
4 m/s, -10 °C	-4.0	3.2	19.3	11.0	15.7	13.5	16.8
8 m/s, +5 °C	-1.1	-0.1	-4.6	-2.3	-4.5	3.0	13.1
8 m/s, -10 °C	-2.2	1.2	-32.6	-5.3	-9.6	7.2	16.9

Table 4.3 shows, that the flow directions calculated by the simplified model are correct with one exception. For a situation with 4 m/s wind speed and +5 °C the maximum difference between the simplified and detailed method is 73.7%, while a situation with 8 m/s and +5 °C gives a maximum difference of 13.1% (not the same flow path). This does not mean that the simplified method is more correct for high wind speeds. If we had a situation with wind effect only, we would observe the same percent differences between the simplified and the detailed method for both 4 and 8 m/s. The differences is an effect of the superposition and there is no general trend depending on either wind speed or temperature differences.

4.3.4 Number of iteration steps

In a calculation made by hand only, the time spent is nearly proportional with the number of iteration steps. Table 4.2 is based on a calculation procedure with 5 iteration steps. If we consider more or less iteration steps, as shown in Table 4.4, this does not change the picture dramatically.

	Flat 1			Flat 2	Flat 3		
	wind	lee	door	door	wind	lee	door
wind (story)							
<i>simplified</i>							
1. step	18.0	-41.2	23.2	40.8	73.5	-88.7	15.2
3. step	18.3	-40.7	22.4	43.7	75.5	-87.2	11.7
6. step	18.4	-40.4	22.0	44.8	76.5	-86.5	10.0
10. step	18.5	-40.3	21.8	45.3	76.9	-86.1	9.2
15. step	18.5	-40.4	22.0	45.3	77.7	-86.0	8.9
<i>detailed</i>	18.5	-40.2	21.8	44.6	76.4	-85.2	8.8
wind + stack							
<i>simplified</i>							
1. step	32.5	12.0	-58.9	-40.5	104.9	-61.1	-104.9
3. step	32.7	12.7	-59.2	-37.3	106.5	-59.4	-105.9
6. step	32.7	13.1	-59.4	-36.0	107.2	-58.6	-106.2
10. step	32.8	13.3	-59.5	-35.4	107.6	-58.1	-106.4
15. step	32.7	13.1	-59.4	-35.4	107.7	-58.0	-106.5
<i>detailed</i>	35.1	14.6	-49.7	-32.8	126.9	-41.7	-85.2

If we increase the number of iteration steps to fifteen the differences for the air flows caused by wind on a story type building are less than two percent. By increasing the number of iterations the approach becomes better and better. This is not clearly the result if we consider flows caused both by wind and stack effect. Increasing the number of iteration steps has no significant effect. The reason is, as mentioned above, the errors incorporated by superimposing flows. In many cases a few iteration steps will be sufficient.

4.3.5 Overall infiltration due to wind

For some applications it might be sufficient to estimate the overall infiltration rate for a building, without determining the individual flow paths. The infiltration rate due to wind for the whole building can be calculated using the permeabilities shown in Fig. 5.1. Each story is hereby treated as a single-zone building.

The envelope permeability ratio epr is given by:

$$epr = \frac{D_{lee, envelope}}{D_{total, envelope}} = \frac{37.3}{81.2} = 0.459$$

The overall infiltration rate due to wind can be calculated using Fig. 3 and the resultant permeabilities listed in Appendix I. For the first story of a story-type building at wind speeds 4 m/s and a pressure distribution according to Krischer and Beck [4], we calculate an infiltration rate of 133 m³/h. This value is only 3.8% higher than the value calculated with a detailed infiltration program taking the internal partitions into consideration. The overall infiltration rate for the same house calculated as a shaft-type building is only 0.3% lower than the calculated rate for the story-type building (Table 4.5).

case	simplified model	detailed model	difference in %
1st floor, story-type	133	128	3.8
8th floor, story-type	185	183	1.1
total build., story-type	1205	1175	2.6
total build., shaft-type	1205	1172	2.8

4.3.6 Other permeabilities - flow directions

What happens if one initially guess the wrong flow direction? Will this show up directly in a hand calculation? Suppose the leeward permeability in flat 3 is zero (with the same wind direction etc.), then we will have an airflow going from the windward side of flat 3 through the staircase, through flat 1 and flat 2 and out on the leeward side of flat 1 and flat 2. The leeward permeability for the staircase will increase during the iteration process. The resultant permeabilities are found using Equation 17.

No permeability on the leeward side of flat 3 is an extreme case, and it is obvious, that the flow then will go from the flat to the staircase. We often have situations with flow directions that are not obvious. For example, the permeability on the leeward side of flat 3 decreases from the initial value of 17.1, then at some point we will observe that the rpr-difference (rpr-value flat 3 minus rpr-value staircase) becomes negative. The airflow will then go in the other direction. The new flow directions are shown in Fig. 5.7.

A detailed study of this phenomena is presented in Table 4.6, where calculations with the simplified model are compared with those from the detailed model. All calculations with the simplified model are done with 5 iteration steps. Further studies have shown, that five iteration steps are sufficient after the change of air flow direction. If we are

mostly concerned about the overall flow for each flat, a calculation with 5 steps or less will be usually sufficient.

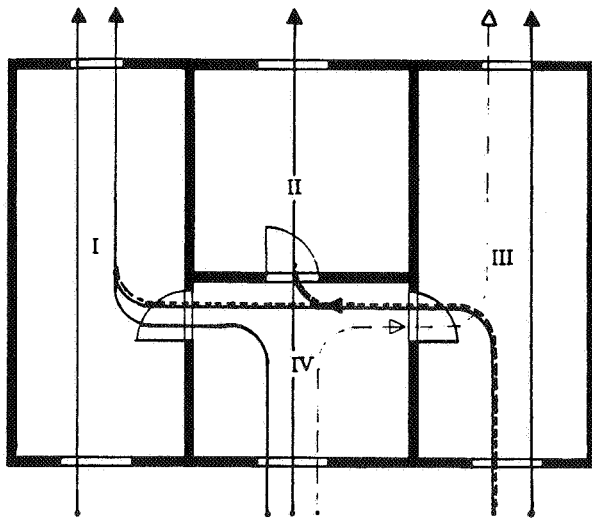


Fig. 5.7: Air flows - leeward permeability of flat 3 $< 12.0 [m^3/(hPa^n)]$

Table 4.6: Air mass flows - variable permeability D_{lee} , flat 3 (1th floor) [kg/h], $v_a = 4 \text{ m/s}$, $t_{out} = -10 \text{ }^\circ\text{C}$, Wind perpendicular to facade, Story type building							
	wind	Flat 1 lee	door	Flat 2 door	wind	Flat 3 lee	door
<i>simplified</i>							
$D_{lee} = 18$	18.4	-40.5	22.1	44.5	76.2	-86.7	10.4
$= 13$	17.9	-41.5	23.6	45.9	67.0	-71.0	4.0
$= 12$	17.8	-41.7	24.0	46.3	64.4	-66.7	2.3
$= 11$	17.6	-42.0	24.4	46.7	61.8	-62.3	.5
$= 10$	17.5	-42.2	24.7	46.9	58.9	-57.7	-1.1
$= 9$	17.4	-42.5	25.1	47.3	55.9	-53.0	-2.9
$= 1$	15.4	-45.9	30.5	52.0	29.1	-9.8	-22.3
<i>detailed</i>							
$D_{lee} = 18$	18.5	-40.2	21.8	44.6	76.4	-85.2	8.8
$= 13$	17.7	-41.4	23.7	46.2	68.5	-68.5	0.1
$= 12$	17.5	-41.7	24.2	46.7	66.6	-64.0	-2.5
$= 11$	17.3	-42.0	24.7	47.1	64.4	-59.5	-4.9
$= 10$	17.1	-42.3	25.2	47.5	62.0	-54.9	-7.1
$= 9$	16.9	-42.6	25.7	47.9	59.5	-50.1	-9.4
$= 1$	15.5	-44.7	29.2	50.8	32.9	-6.3	-26.6

The most common reason for guessing the direction of a particular flow wrong, is lack of information on internal flow paths at the beginning of the iteration procedure. Usually, this occurs only in zones with opr-values lower than 0.5. The calculation procedure would then indicate the wrong directions after one or two steps.

Using the simplified model, Table 4.6 shows, that the air flow through the door of flat 3 changes direction at values for D_{lee} between 10 and 11. This corresponds to values between 12 and 13 if the detailed model is used. As the leeward permeability decreases, the air flows through the doors and leeward side of flat 2 and 3 increase.

4.3.7 Wind parallel to facade

Until now we only have been handling wind perpendicular to the main facade (west). To show how to calculate air flows for wind flowing parallel to the main facade, the permeability distribution has been changed as indicated on Fig. 5.8. The permeability value for each of the three flats has been kept the same. The possible flow paths for a story type building is shown in Fig. 5.8.

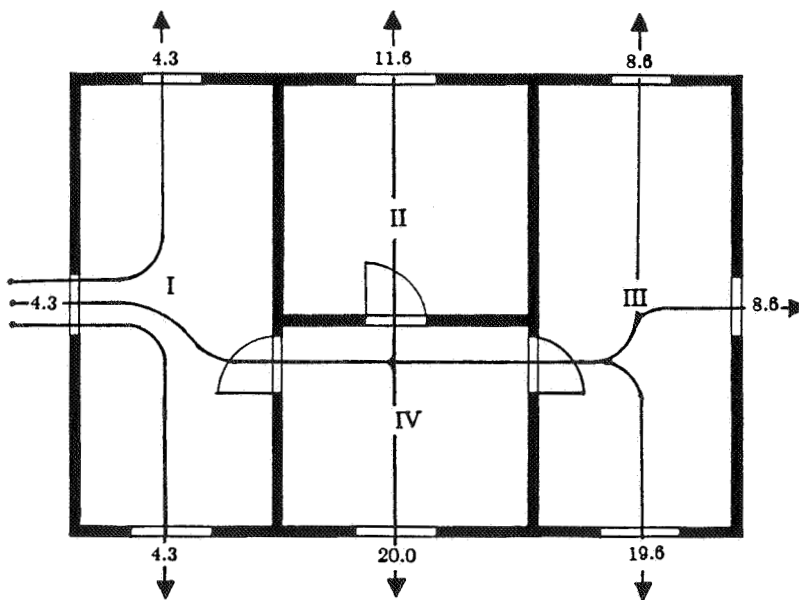


Fig. 5.8: Flow paths - wind parallel to the facade

The main problem is to find the resultant permeabilities for the flow paths going from flat 1 through the other zones. As we use the same $c_{lee} = -0.3$ for all sides of the building except the windward side, this is a rather straight forward job:

- 1) - summarize the leeward permeabilities in zone III, and find $D_{res,III}$ for $D_{door,III}$ and $\sum D_{lee,III}$.

- 2) - find $D_{res,II}$ for $D_{door,II}$ and $D_{lee,II}$.
- 3) - summarize $D_{res,III}$, $D_{res,II}$ and $D_{lee,IV}$; and find $D_{res,II,III,IV}$ for $D_{door,I}$ and $\sum D_{res,II}, D_{res,III}, D_{res,IV}$.
- 4) - split $D_{wind,I}$ in relation to $D_{res,II,III,IV}$, $D_{lee,I,south}$ and $D_{lee,I,north}$.
- 5) - find D_{res} for the part of $D_{wind,I}$ and the respective $D_{lee,I,north}$, $D_{lee,I,south}$ and $D_{res,II,III,IV}$.

This calculation does not involve an iteration procedure, so the correlation between the simplified and the detailed model for either wind or stack effect is good. But as in previous examples, the superimposition of different flows causes an error.

4.4 Other Examples

Calculations are made for a series of different buildings ranging from a single family building to multistory buildings. The results from these calculations confirms the main results presented in detail for the Brunsbuettler building. But there is some differences regarding the modeling of air flows in different zones.

4.4.1 Single family building

This house was chosen at random from a journal [8] presenting 275 new home designs. We consider this house to be a good example of a single family building in the U.S. The floor area is 145 m^2 in the first floor and 55 m^2 for the second floor. The first story with its great room, dining room, family room and kitchen is open to the staircase. Only the master bedroom and the utility/garage are separated by doors. There are no windows or doors on the short side walls of the building. The different permeabilities used in the calculations (see Fig. 7), are stipulated by using the ASHRAE Handbook of Fundamentals [2].

4.4.1.1 Modeling

The main difference from the previous case is that both floors differ in size, design and permeabilities. Therefore,

- The zone including the staircase will include all rooms on the first floor except the master bedroom, utility room and garage. This "stair" zone has openings on both windward and leeward side at the first floor but, no openings on the second floor.
- The natural pressure level z_n is found using Equ. 22.
- Due to the lack of openings on the short sidewalls, there will be no air flows caused by wind parallel to the facade.



FARMHOUSE FLAVOR IN AN ECONOMICAL HOME

PLAN NO. D10G8576 Once inside this home you'll be impressed with its warm cheery fireplace. From the great room you can gain access to the greenhouse and the spacious deck area. The master bedroom has its own fireplace, bath and huge walk-in closet. Upstairs are two more bedrooms and another full bath. total living area first floor 1454 sq ft. second floor 544 sq ft and the greenhouse 125 sq ft

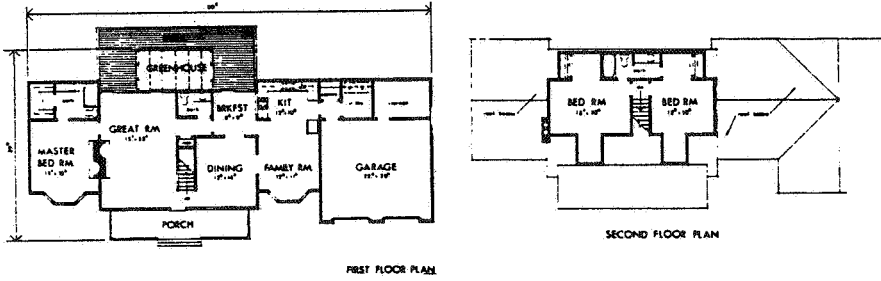


Fig. 6: Two-story single family building

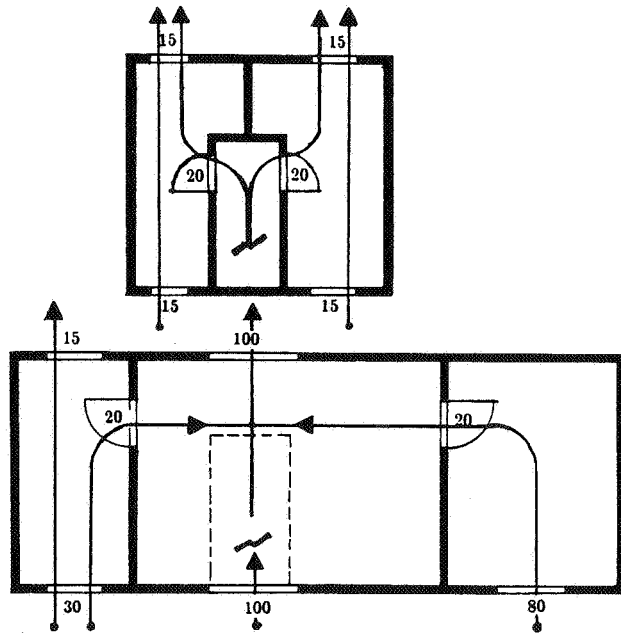


Fig. 7: Assumed flow paths - 1. iteration step

The building is divided in five zones; in the first floor the staircase together with living room, dining room and kitchen is one zone, master bedroom with the attached bath form one zone, and the and garage and utility room form another zone. In the second story, the stair is part of the staircase zone in the first floor, and each bedroom with bath forms another zone. As we assume uniform wind speed up to ten meters above the ground, there will be no downward airflow in the staircase due to wind effect (i.e. no difference between air flows for the story and the shaft type building). Possible flow paths

are shown in Fig. 7.

4.4.1.2 Results - comments

The air mass flows due to wind and stack effect for $v_o = 4$ m/s and $t_{out} = -10$ °C and wind perpendicular to main facade are shown in Table 5.

Location	Simplified	Detailed	% difference
Zone 1 - Master bedroom			
windward	91.9	95.7	-4.0
lee	-82.0	-76.2	6.1
door	9.9	19.5	-10.0
Zone 2 - Living room			
windward	407.1	358.1	12.8
lee	-419.5	-383.0	9.5
door	12.4	24.9	-3.3
Zone 3 - Garage			
windward	66.6	63.6	4.7
lee	--	--	--
door	66.6	63.6	4.7
Zone 4 & 5 Bedroom			
windward	43.0	47.4	-5.8
lee	-83.8	-76.5	9.5
door	40.8	40.8	0.0

The differences are reasonable and well within acceptable limits. The results shown in Table 5 assume that the doors between the different zones are closed.

4.4.2 Small multifamily building

This building is a three-story apartment building with a central fire wall built in Chicago in the 1920s [9]. The arrangement of apartments is similar to a lot of buildings from this period, with symmetrical floor plans having a common entry hall and a central stair in front, and separate balconies and outside stairs in back. The leakage areas were assumed to be evenly distributed for the different stories, and Fig. 9 shows the distribution of permeabilities and assumed flow paths.



Fig. 8: Three stories building, plan and elevation (Bosworth, Chicago)

4.4.2.1 Modeling

The Bosworth building is not a simple square box; the front has oriel windows and the back of the building has closed balconies and outside stairs. Our models get rather complicated if we want to model all this in detail, so we have made the simplification shown in Fig. 9. The building is reduced to a square box; we use the same pressure coefficients for all leaks on one main sides. In the case with wind perpendicular to the street facade we assume a uniform wind pressure distribution over the whole facade. In order to compare the results of the two models, these simplifications were also done for calculations with the detailed model.

As described before the same permeabilities have been used for all floors. The leakage area between the two flats on each floor is taken into account, but not vertical leaks between flats on different floors. Due to identical permeabilities for the two flats on each floor, there will be the same pressures in flats on the same floor, both for stack effect and wind perpendicular to the facade. In one case of wind parallel to the main facade (from west), the pressures will be different in the two flats. This will cause an air flow directly from flat 1 to flat 2.

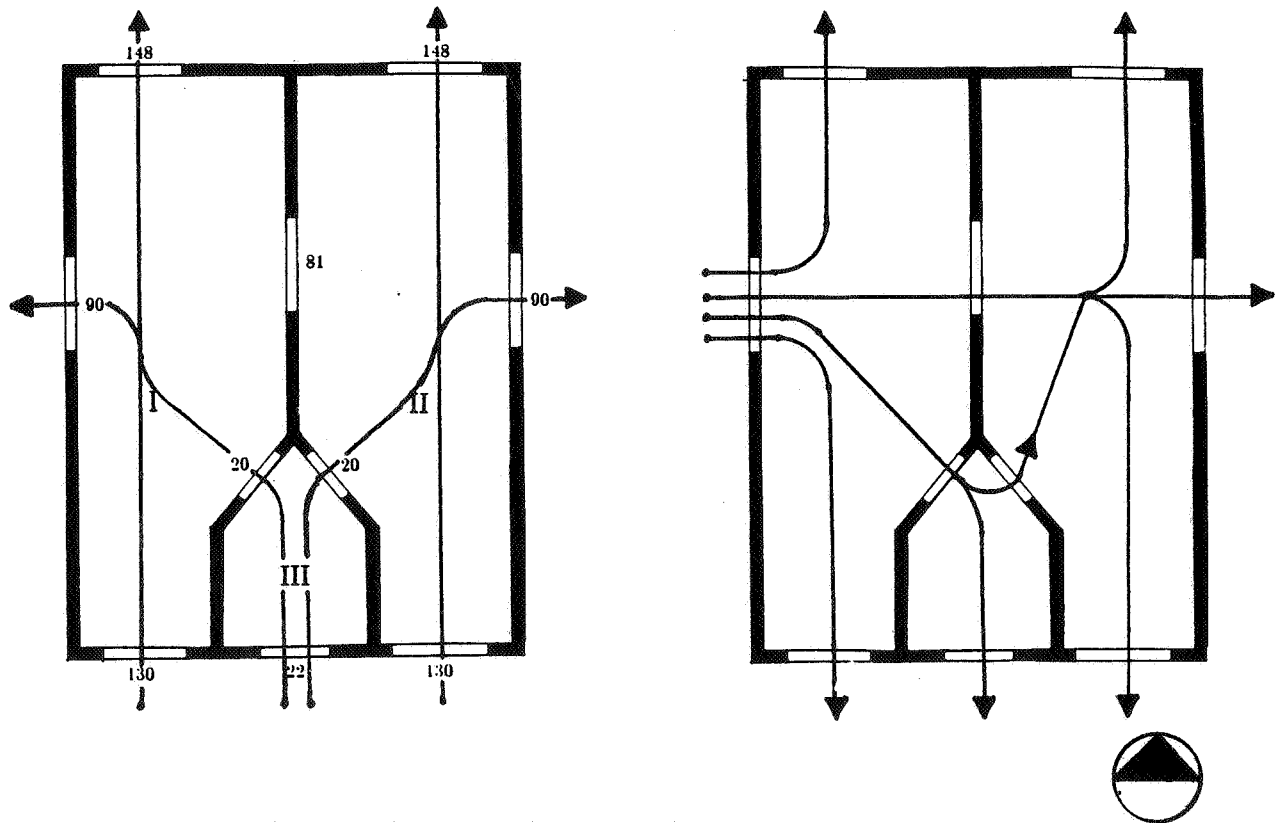


Fig. 9: Assumed flow paths for wind from south and west

4.4.2.2 Results - comments

Table 6 shows air mass flows due to wind and stack effect for wind flows perpendicular to the main facade, whereas Table 7 shows air mass flows for wind parallel to the main facade. Total air mass flow due to wind and stack from the simplified and the detailed model as well as the differences between them, are presented in each table.

Table 6: Air mass flow due to wind and stack, $v_a = 4m/s$, $t_{out} = -10^\circ C$, Wind perpendicular to facade				
Story	Lobby	Flat 1=Flat 2		
		Wind	Lee	Door
<i>Simplified</i>				
1	137.3	733.8	-674.0	-34.0
2	98.3	731.0	-681.2	49.1
3	48.7	728.2	-688.5	92.3
<i>Detailed</i>				
1	131.5	751.1	-736.3	-14.8
2	88.9	728.8	-782.2	53.4
3	35.9	732.7	-822.2	89.5
<i>Difference %</i>				
1	4.4	-2.3	-8.3	2.6
2	8.8	.3	-12.9	-0.5
3	7.2	-.4	-16.3	0.4

Table 7: Air mass flow due to wind and stack, $v_a=4m/s$, $t_{out} = -10^\circ C$, Wind parallel to facade							
Story	Lobby	Wind	Flat 1		Wall	Flat 2	
			Lee	Door		Lee	Door
<i>Simplified</i>							
1	63.8	601.0	-441.6	-77.2	118.7	-98.2	98.2
2	-13.6	599.2	-452.9	-26.4	118.7	-132.0	132.0
3	-71.1	597.4	-463.9	55.0	118.7	-161.9	161.9
<i>Detailed</i>							
1	70.1	619.6	-427.6	-70.5	121.5	-64.5	-57.1
2	-18.6	613.1	-463.0	-24.9	125.3	-138.7	-13.4
3	-75.7	615.8	-527.1	48.9	137.5	-203.5	66.0
<i>Difference %</i>							
1	-3.0	-3.0	2.3	1.1	-2.3	27.7	4.7
2	-9.0	-2.3	-1.7	0.2	-5.3	-4.8	0.5
3	-2.4	-3.0	-10.3	1.0	-13.7	-20.4	3.1

Tables 6 and 7 show that the flow directions are the same for all flows calculated either with the simplified or the detailed model. The high permeabilities for windows compared with those for the doors, makes the air flows through the flats more dominated by wind forces than the stack effect.

For wind perpendicular to the facade we find rather small differences between the models in mass flows going through the flats. The difference for the staircase is for the third floor 35.7%, but this is mainly caused by low mass flows in the staircase compared to mass flows through the flats. Assuming no adjacent buildings, the air mass flows through flat 2 are very low for wind from west (parallel to the main facade). This causes differences up to 50%. Air flows coming in from the windward side of flat 1 (west) will mainly leave this zone through the leeward sides. Only a small air flow is transferred to the adjacent flat.

4.5 Large multifamily buildings

The large apartment building contains 4 flats on each of the eight floors. We have studied different situations; a) the staircase has one wall with openings to the outside (called: open staircase), and b) the staircase has no exterior wall (closed staircase). Permeabilities for the different zones are shown on the respective simplified floor plans.

Compared to the building at Brunsbuettler Damm we have a building with openings to all 4 sides. For wind perpendicular to the main facade (from south), there are no main differences in the air flows between the two models. As the pressure coefficient is the same for all leeward sides, the parallel permeabilities can be added. Flow paths through flat 1 and 4 will either go directly from the windward to the leeward side (on west or east side) or from windward side to the stair and from there to the leeward side of the flats. Flows through flat 2 and 3 will always go from stair zone to leeward side. The flows for the leeward side of each zone are calculated separately, but are presented as the total leeward

flow for each zone in Table 8 and Table 9.

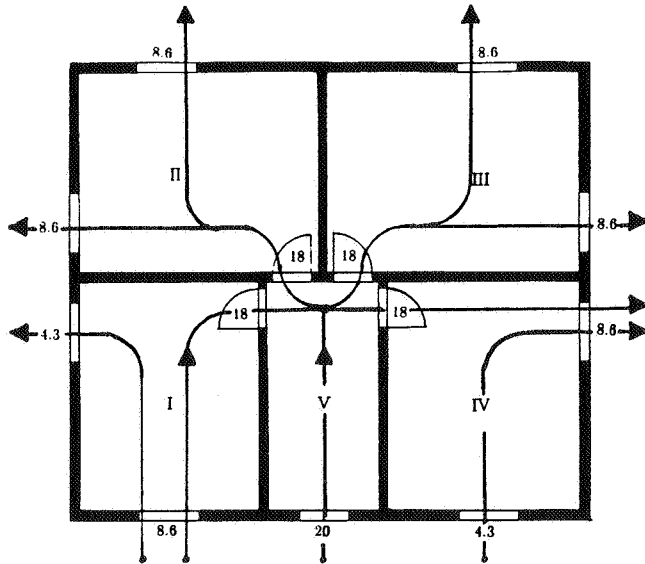


Fig. 10: Principal sketch - 4 flats / open staircase

Table 8: Air mass flow due to wind and stack, Wind perpendicular to facade, $v_a = 4 \text{ m/s}$, $t_{out} = -10^\circ\text{C}$, Open staircase (Flat 2 and 3 similar)

Story	Lobby	Flat 1			Flat 2,3		Flat 4	
		Wind	Lee	Door	Lee	Wind	Lee	Door
<i>Simpl.</i>								
1	206.7	64.2	4.7	-75.8	65.5	36.0	25.4	-69.4
2	180.3	55.9	-8.3	-61.5	45.1	32.1	9.9	-54.4
3	151.9	46.9	-15.0	-45.4	18.0	28.0	-16.2	-36.8
4	121.7	37.3	-21.0	-25.1	-29.9	23.8	-30.8	-11.8
5	94.6	28.5	-28.9	16.4	60.4	21.0	-46.7	30.3
6	61.9	17.8	-35.6	40.5	83.9	17.7	-59.9	51.8
7	13.1	-2.0	-41.6	58.6	104.3	14.1	-71.9	69.3
8	74.2	-18.9	-47.1	74.2	122.6	9.7	-82.2	84.7
<i>Detal.</i>								
1	200	68	4	-72	50	37	21	-58
2	170	60	-7	-53	26	33	3	-36
3	138	51	-13	-38	-20	29	-18	-11
4	104	41	-19	-22	-46	23	-34	11
5	80	34	-26	-8	-66	20	-47	27
6	51	23	-32	9	-84	17	-58	41
7	-3	13	-38	25	-100	14	-68	54
8	-47	-1	-42	43	-116	11	-77	66

If the staircase has no direct permeabilities to the outdoor (Fig. 11), we will experience less pressure differences between the flats and the staircase, and therefore lower air flows. Table 9 gives the air flows for the same outdoor temperature and wind speed as shown in Table 8. The calculation does not include any flow resistance between the shaft and the floor landing.

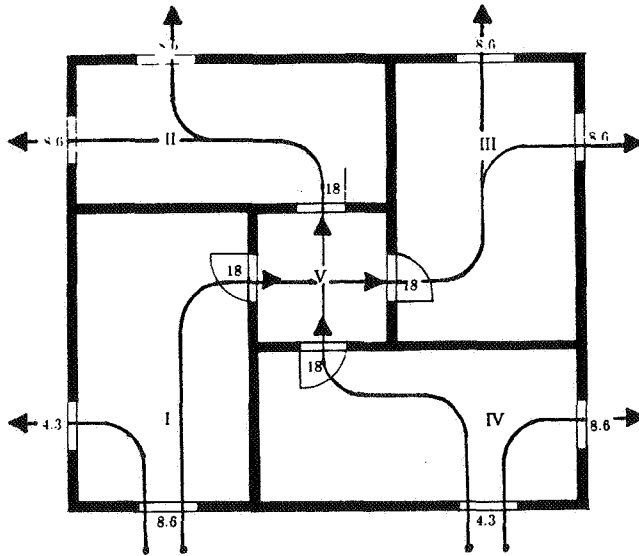


Fig. 11: Principal sketch - 4 flats / closed staircase

Table 9: Air mass flow due to wind and stack, Wind perpendicular to facade $v_a = 4 \text{ m/s}$, $t_{out} = -10^\circ\text{C}$, Closed staircase								
Story	Lobby	Wind	Flat 1		Flat 2,3 Lee	Wind	Flat 4	
			Lee	Door			Lee	Door
<i>Simplified</i>								
1	-	58.1	37.5	-70.3	73.4	49.0	35.6	-66.4
2	-	49.3	33.7	-55.3	54.4	39.3	31.6	-50.9
3	-	39.7	29.7	-38.0	31.2	28.3	27.4	-32.6
4	-	29.5	26.0	-15.6	-13.8	14.8	23.5	-5.1
5	-	21.5	25.0	20.4	-41.8	-7.9	21.9	28.3
6	-	11.0	23.7	39.4	-62.2	-21.9	20.1	46.2
7	-	-9.3	22.2	54.6	-79.6	-32.4	18.0	61.2
8	-	-20.8	20.4	68.0	-95.4	-41.4	15.6	74.6

For wind direction perpendicular to the main facade (from west), flat 1 and 2 will have a windward side, flat 3 and 4 together with the lobby will completely be on the leeward side.

5. SUMMARY

Buildings are classified into different categories based on their air permeability distribution. This is helpful in reducing the input data and limiting the different cases that might occur. For the simplification procedure we assume equal flow pattern for all permeabilities. Resultant permeabilities can be calculated for permeabilities in series and parallel arrangement. We can superimpose flows caused by different physical phenomena.

The examples show that the simplified method can be used to predict air mass flows within reasonable accuracy for different types of buildings. We are able to calculate air flows due to wind or stack effect within a few percent difference from results calculated with a detailed model. We might expect larger differences when superimposing flows caused by different effects. The best results are for superimposition of flows which have the same direction.

In all examples have we:

- 1) - calculated the flows for the story-type building
- 2) - calculated vertical flows due to wind
- 3) - calculated the flows due to thermal buoyancy
- 4) - superimposed the different flows

If the total air flow per zone is more important than the air flow for a particular flow path, the first few iteration steps already give a reasonable result. However, if the value for a particular flow path is important, the number of necessary steps is determined by the smallest rpr-differences.

In situations where the air flow direction is different from that assumed by using the opr-values, the share of the windward side permeability related to the resultant leeward permeability can be calculated by taking the leeward permeabilities of the considered zone and the rpr-value differences into account.

Iteration procedures are only necessary, if one can not calculate the rpr-differences for different zones immediately, and has to start using the opr-values. For the flows caused by stack effect and by vertical wind forces, the resultant permeabilities can be calculated for permeabilities in series and parallel arrangement directly. No iteration process is necessary.

Two important parameters -- the pressure field around the building and the permeability distribution of the external and internal building components -- are only roughly estimated. Both of these parameters must be determined for proper evaluation and application of models. With the growing proliferation of wind tunnel studies, it may soon be possible to predict the pressure field around a building. The need remains, however, for a multizone pressurization method capable of yielding necessary information about a building's air permeability distribution. Until both input parameters can be determined, all multizone infiltration models will be handicapped.

6. ACKNOWLEDGEMENTS

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Appendix I:
 Resultant Permeability for two Permeabilities in Series Arrangement (Common Exponent = 2/3)

D_{small}/D_{large}	D_{res}/D_{large}	D_{small}/D_{large}	D_{res}/D_{large}	D_{small}/D_{large}	D_{res}/D_{large}
1.0000	0.6299	0.7336	0.5300	0.4672	0.3884
0.9946	0.6283	0.7283	0.5276	0.4619	0.3850
0.9893	0.6266	0.7229	0.5252	0.4565	0.3816
0.9840	0.6249	0.7176	0.5228	0.4512	0.3782
0.9787	0.6231	0.7123	0.5204	0.4459	0.3748
0.9733	0.6214	0.7069	0.5180	0.4406	0.3713
0.9680	0.6197	0.7016	0.5155	0.4352	0.3678
0.9627	0.6179	0.6963	0.5130	0.4299	0.3643
0.9574	0.6161	0.6910	0.5105	0.4246	0.3608
0.9520	0.6144	0.6856	0.5080	0.4192	0.3572
0.9467	0.6126	0.6803	0.5055	0.4139	0.3536
0.9414	0.6108	0.6750	0.5030	0.4086	0.3500
0.9360	0.6090	0.6697	0.5004	0.4033	0.3464
0.9307	0.6071	0.6643	0.4978	0.3979	0.3427
0.9254	0.6053	0.6590	0.4952	0.3926	0.3390
0.9201	0.6035	0.6537	0.4926	0.3873	0.3353
0.9147	0.6016	0.6483	0.4900	0.3820	0.3316
0.9094	0.5997	0.6430	0.4873	0.3766	0.3279
0.9041	0.5978	0.6377	0.4846	0.3713	0.3241
0.8987	0.5959	0.6324	0.4819	0.3660	0.3203
0.8934	0.5940	0.6270	0.4792	0.3606	0.3164
0.8881	0.5921	0.6217	0.4765	0.3553	0.3126
0.8828	0.5901	0.6164	0.4738	0.3500	0.3087
0.8774	0.5882	0.6110	0.4710	0.3447	0.3048
0.8721	0.5862	0.6057	0.4682	0.3393	0.3009
0.8668	0.5842	0.6004	0.4654	0.3340	0.2969
0.8615	0.5822	0.5951	0.4626	0.3287	0.2929
0.8561	0.5802	0.5897	0.4597	0.3233	0.2889
0.8508	0.5782	0.5844	0.4568	0.3180	0.2849
0.8455	0.5762	0.5791	0.4540	0.3127	0.2808
0.8401	0.5741	0.5738	0.4510	0.3074	0.2767
0.8348	0.5721	0.5684	0.4481	0.3020	0.2726
0.8295	0.5700	0.5631	0.4452	0.2967	0.2685
0.8242	0.5679	0.5578	0.4422	0.2914	0.2643
0.8188	0.5658	0.5524	0.4392	0.2861	0.2601
0.8135	0.5637	0.5471	0.4362	0.2807	0.2559
0.8082	0.5615	0.5418	0.4332	0.2754	0.2517
0.8028	0.5594	0.5365	0.4301	0.2701	0.2474
0.7975	0.5572	0.5311	0.4270	0.2647	0.2431
0.7922	0.5550	0.5258	0.4239	0.2594	0.2388
0.7869	0.5528	0.5205	0.4208	0.2541	0.2345
0.7815	0.5506	0.5151	0.4177	0.2488	0.2301
0.7762	0.5484	0.5098	0.4145	0.2434	0.2257
0.7709	0.5462	0.5045	0.4113	0.2381	0.2213
0.7656	0.5439	0.4992	0.4081	0.2328	0.2168
0.7602	0.5416	0.4938	0.4049	0.2274	0.2123
0.7549	0.5393	0.4885	0.4016	0.2221	0.2078
0.7496	0.5370	0.4832	0.3983	0.2168	0.2033
0.7442	0.5347	0.4779	0.3950	0.2115	0.1988
0.7389	0.5324	0.4725	0.3917	0.2061	0.1942

Appendix II

Iteration step : #2

DESCRIPTION	#	FLAT # 1	FLAT # 2	FLAT # 3	STAIR (#4)
D_{stair}	1	6.0	10.6	3.5	---
D_{door}	2	18.	18.	18.	---
$D_{res:\#1,\#2}$	3	5.32	8.26	3.27	---
D_{wind}	4	4.3	---	19.6	20.
D_{lee}	5	8.6	11.6	17.1	10.35
$D_{lee,stair}$	6	4.76	11.6	2.44	---
$D_{res:\#2,\#6}$	7	4.37	8.79	2.36	---
$D_{res:\#3,\#6}$	8	---	---	---	---
$D_{res:\#4,(\#5-\#6)}$	9	---	---	---	---
$rpr \frac{\#5}{\#3+\#4+\#5}$	10	0.52	0.68	0.44	0.34
rpr-difference	11	0.18	0.34	0.10	---
share of D_{stair}	12	5.8	11.0	3.3	---

Iteration step : #3

DESCRIPTION	#	FLAT # 1	FLAT # 2	FLAT # 3	STAIR (#4)
D_{stair}	1	5.8	11.0	3.2	---
D_{door}	2	18.	18.	18.	---
$D_{res:\#1,\#2}$	3	5.19	8.48	3.05	---
D_{wind}	4	4.3	---	19.6	20.
D_{lee}	5	8.6	11.6	17.1	11.5
$D_{lee,stair}$	6	4.7	11.6	2.3	---
$D_{res:\#2,\#6}$	7	4.3	8.79	2.3	---
$D_{res:\#3,\#6}$	8	3.1	6.1	1.7	---
$D_{res:\#4,(\#5-\#6)}$	9	2.6	---	10.6	---
$rpr \frac{\#5}{\#3+\#4+\#5}$	10	0.51	0.65	0.44	0.37
rpr-difference	11	0.14	0.28	0.07	---
share of D_{stair}	12	5.7	11.4	2.9	---

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 9

USE OF STATISTICS FOR PREDICTING DISTRIBUTION OF AIR
INFILTRATION

ANKER F. NIELSEN

Norwegian Building Research Institute
Division Trondheim
Høgskoleringen 7

7034 TRONDHEIM NTH
NORWAY

SUMMARY

Calculation of air infiltration in a large number of cases can give information of expected variations in yearly air change and energy consumptions. As model is used the equivalent leakage area model written in a spreadsheet computer program. For a typical Norwegian house an analysis of the influence of some parameters is made. The influence of climate is found to be small, if we compare the mean yearly air change for towns in Norway. Prediction of air infiltration is made from known variations in indoor temperature, 50 Pa pressurization air change and leakage and pressure characteristics. 500 simulations with random generated normally distributed numbers are done. The mean yearly air change has been found to be 0,24 in Oslo. But 10% will have values above 0,33. Regression shows a good correlation between 50 Pa pressurization air change and the mean yearly value. A good prediction of the mean yearly air change can therefore be based on the pressurization test without exact knowledge of other parameters. The simulation method can be used on more complicated and correct models to find out how uncertain knowledge of the parameter will influence the final results.

1. INTRODUCTION

Measurements of air infiltration from similar buildings will in most cases not give the same results. This is caused by variations in leakage characteristics and climatic conditions. For measurements of a larger number of houses it is impractical to make detailed measurements and calculations. Instead we can use statistical methods. For each important parameter we can assume variations and use this in a model. If we then make a large number of calculations we will find the typical distribution of air infiltration.

The method was originally made for prediction of moisture condensation and drying in constructions. Later it has been used to predict variations in total energy consumption in occupied buildings, where the occupants' behavior can only be estimated. Variations in energy consumption from 50% above to 50% below the mean value is quite normal. The results are found in reference 1.

In this paper we are only interested in the infiltration given as air change and energy consumption for heating the infiltrated air.

2. EQUIVALENT LEAKAGE AREA (ELA) ALGORITHM

The method was developed at Lawrence Berkeley Laboratory to predict the change in infiltration rate with retrofit and other changes in building envelope. We use this model as it is widely known and gives realistic values without too much calculation time. The model is simplified with few parameters:

1. Leakage of structure - measured with pressurization
2. Ratio of floor/ceiling leakage to wall leakage
3. Internal/external temperature difference
5. Wind speed
6. Terrain class
7. Shielding class

In this paper we will not describe the model in detail. A full description is found in AIVC (ref. 2): Air Infiltration Calculation Techniques - An Applications Guide (1986). The model is written on a spreadsheet computer program (SYMPHONY ref. 3) for personal computer. Using spreadsheet with graphics makes it easy to perform parameter variations and statistical analysis.

3. NORWEGIAN BUILDING

As a standard case we use a building of 120 m² with 2 floors and a leakage of 4 air changes per hour at 50 Pa overpressure. This is the maximum allowed leakage in small houses. The leakage in the ceiling is 0,38 of the total. The leakage in the floor is 0,16 of the total. The rest is in the walls. The indoor temperature is 21 °C. The flow exponent is 0,7. The terrain is urban. The shielding coefficient is 0,3 as for light local shielding with few obstructions.

A few calculations with parameter variations have been made and the results plotted. Figure 1 shows curves for the calculated air change versus the wind speed. Each curve is for different temperature differences over the envelope. Typical Norwegian houses have infiltration air change between 0,1 and 0,4.

All other parameter analysis are made with climate from Oslo. We use a monthly calculation and need mean wind speed and temperature. The result from the calculation is either the mean yearly air change or the yearly energy consumption. In both cases only for the infiltration air not the

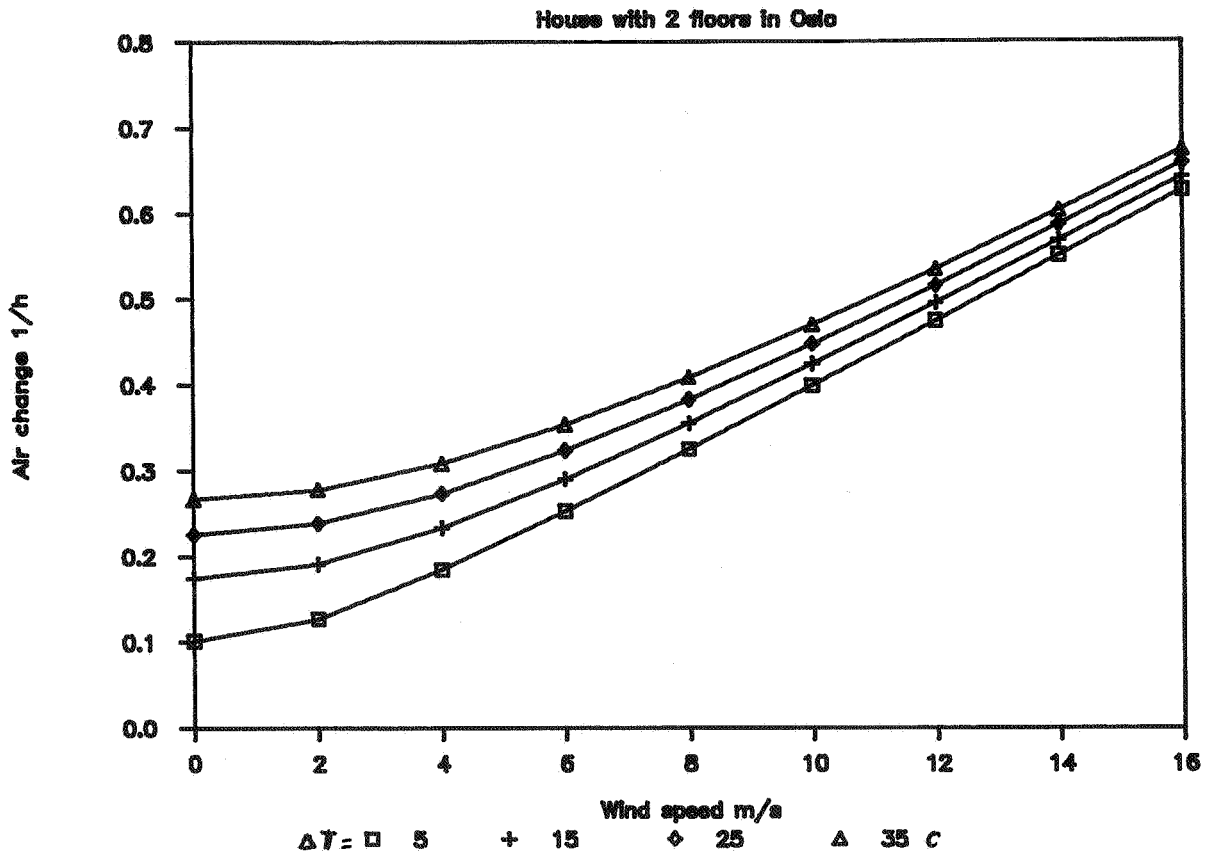


Figure 1. Infiltration air change (1/h) in dependence of wind speed (m/s) and temperature difference (C).

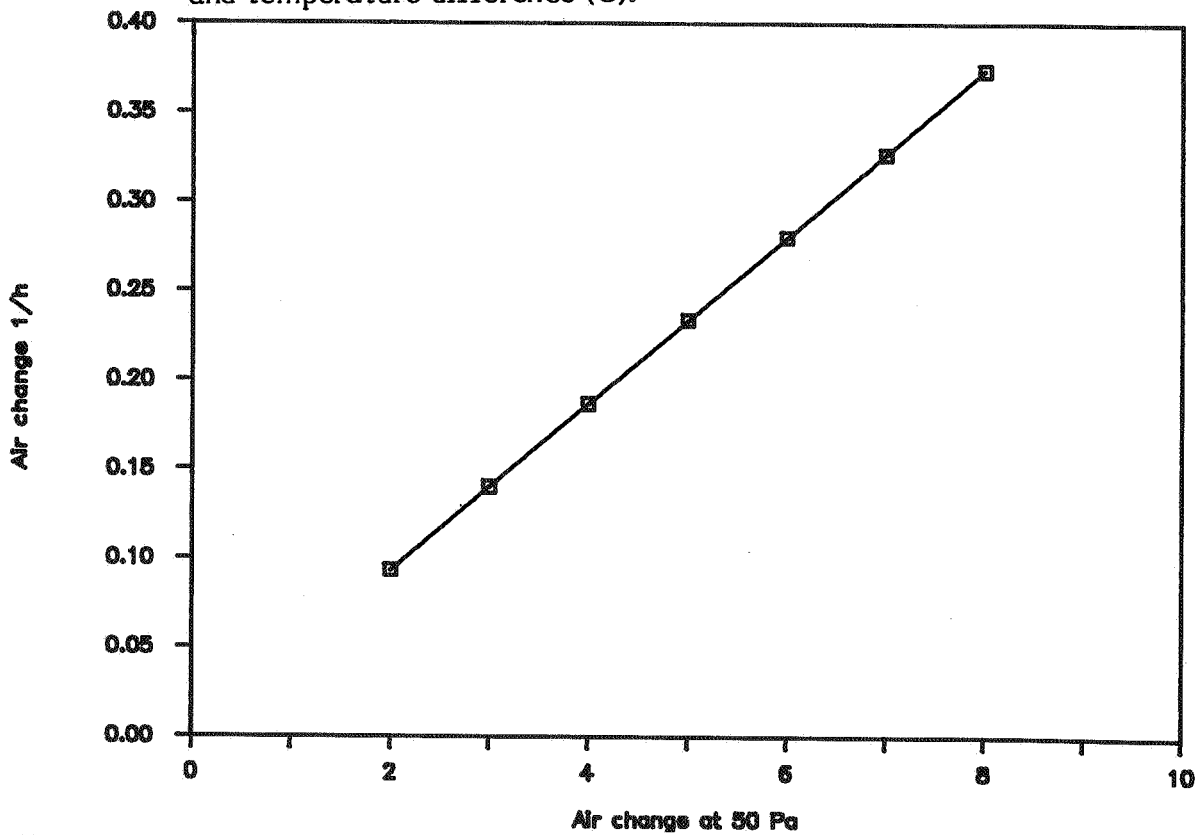


Figure 2. Yearly mean air change (1/h) in dependence of air change (1/h) at 50 Pa pressurization.

total ventilation. The most important parameter in the model is the measured air change at 50 Pa overpressure. Figure 2 shows the variation in the mean yearly air change in dependence of the pressurization air change. For the pressurization air change range from 2 to 8 will infiltration range from 0,1 to 0,4. Parametric analysis are made on other parameters as well but we will only show the dependence of the terrain type (figure 3). The variations are small.

4. CLIMATE VARIATIONS

In a country like Norway there are large variations in climate and it can be expected that it will influence the measured and calculated infiltration.

Figure 4 gives the yearly mean outdoor temperatures in towns in Norway. The towns are ordered from south to north with the most southerly first.

Figure 5 shows the mean yearly wind speeds. Large variations are seen. Typical towns in the inland have low temperature and low wind speed, such as Nesbyen, Røros and Kautokeino. Towns at the coast have high temperature and high wind speed, such as Kristiansand, Bergen, Kristiansund and Vardø.

Figure 6 shows the mean yearly air change for the same building in the various towns. It is a little surprising that the values are so alike. Only Vardø has higher air change. The total infiltration is nearly constant but at the coast is the wind effect dominant and in the inland the stock effect.

Figure 7 shows the yearly energy consumption for infiltration for the towns. These values are not as constant as the air change, because the energy consumption is more dependent on the outdoor temperature. The inland towns with low temperatures Nesbyen, Røros and Kautokeino have the highest energy consumption. The results of this calculation with different climates show that for a statistical analysis we only need one town to get the correct variations in the air change. If we will get the variations in energy consumption, we can make the calculation for one town and later make a transformation to the other climates.

5. NORWEGIAN MEASUREMENTS

The Norwegian Building Research Institute made in 1979 measurements in single family houses in the southern part of Norway (ref. 4). The leakage was measured at 50 Pa overpressure. The lowest value found was 2,0 and the highest 8,0. The mean leakage was calculated to be 4,7 air changes per

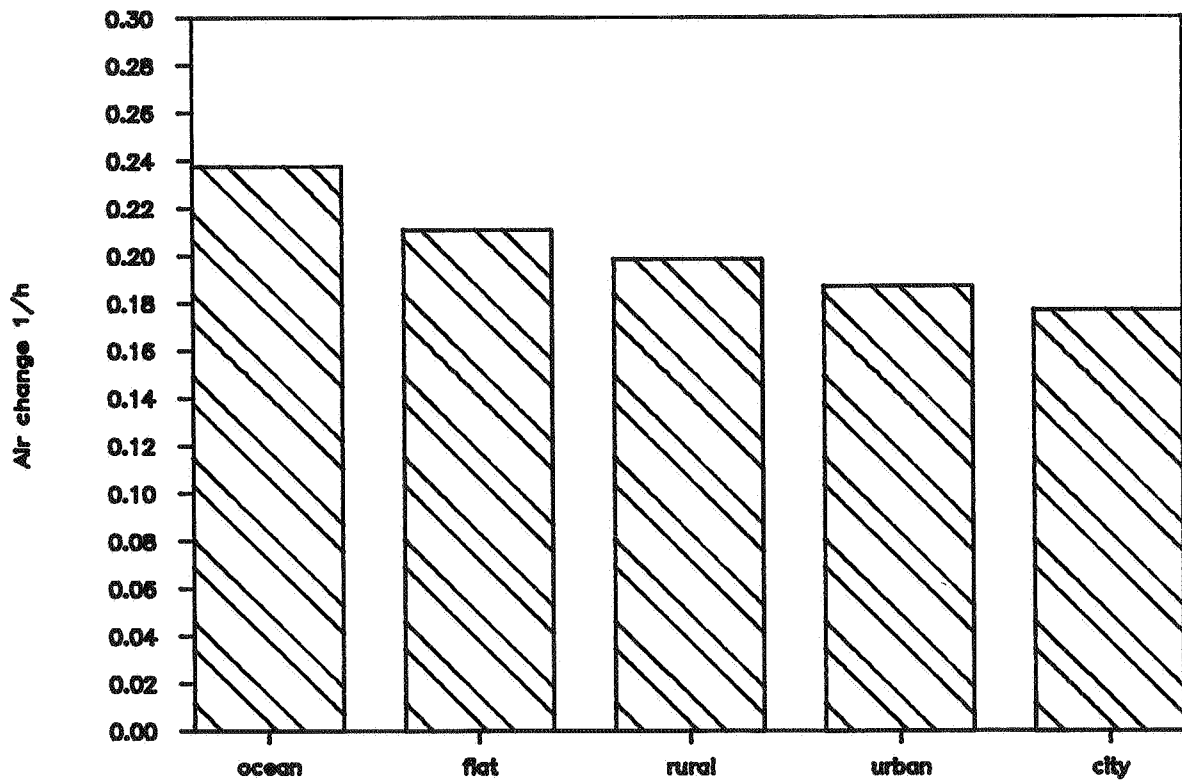


Figure 3. Yearly mean air change (1/h) for different terrain types in the ELA-model.

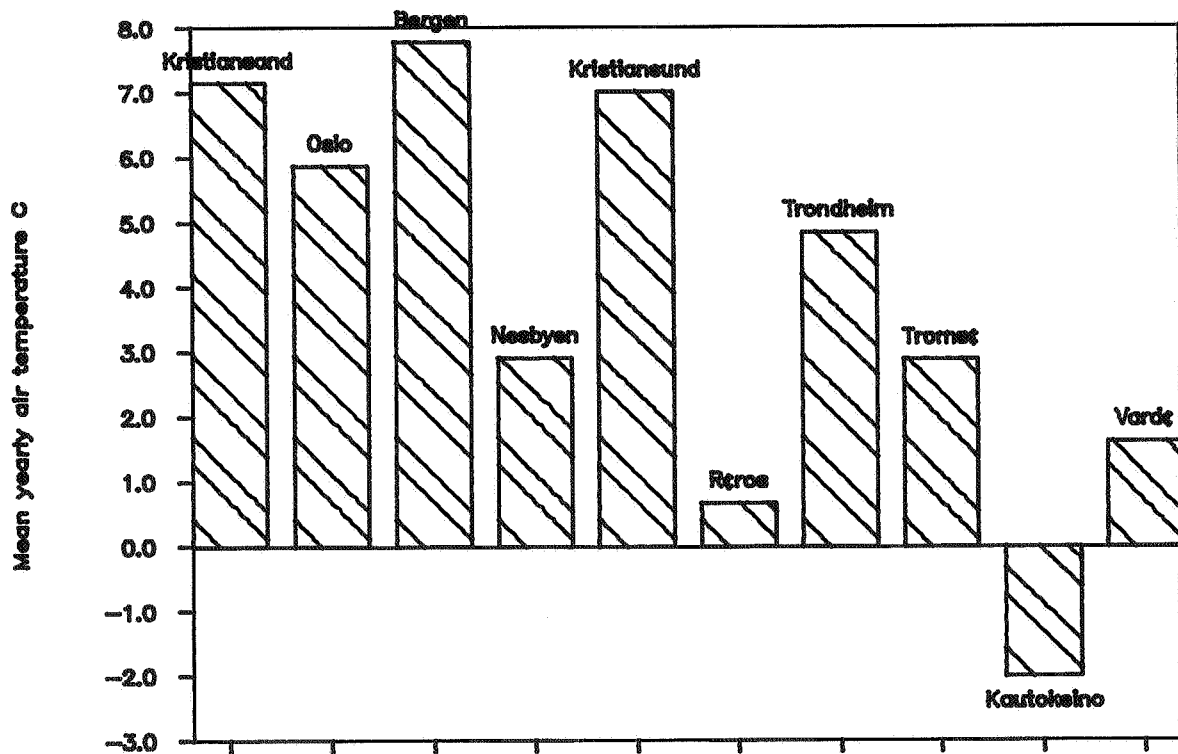


Figure 4. Yearly mean air temperature (C) for towns in Norway

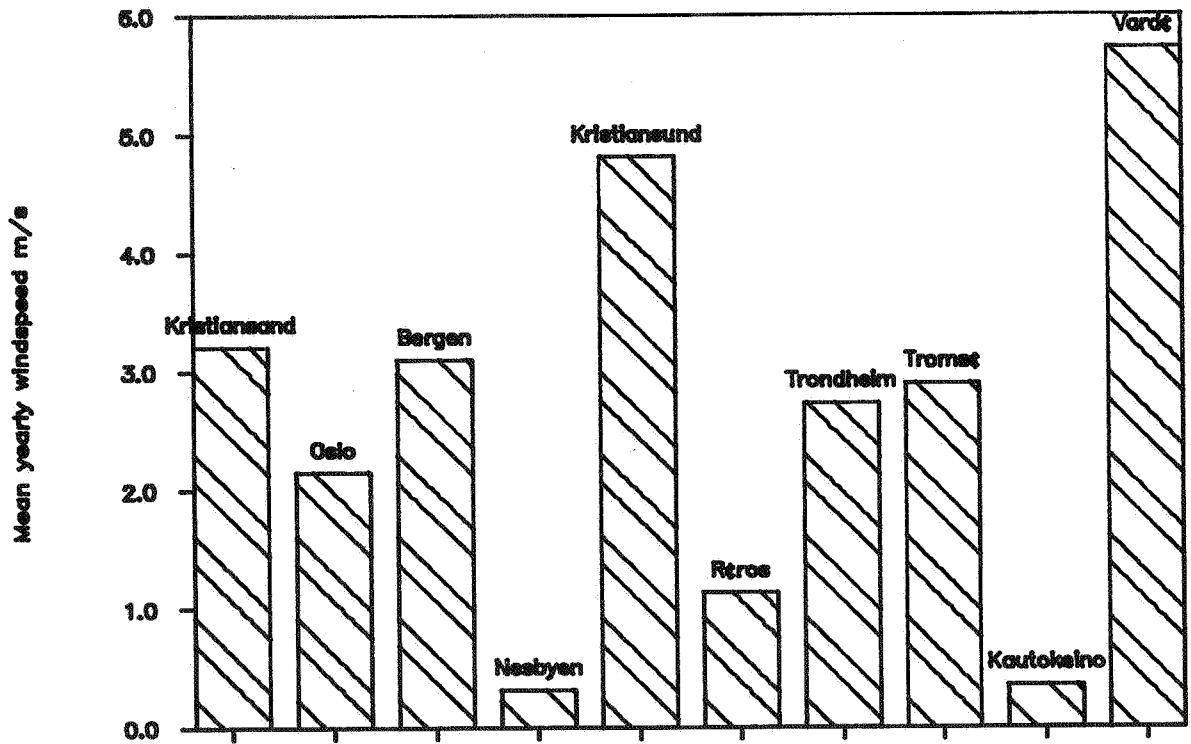


Figure 5. Yearly mean wind speed (m/s) for towns in Norway

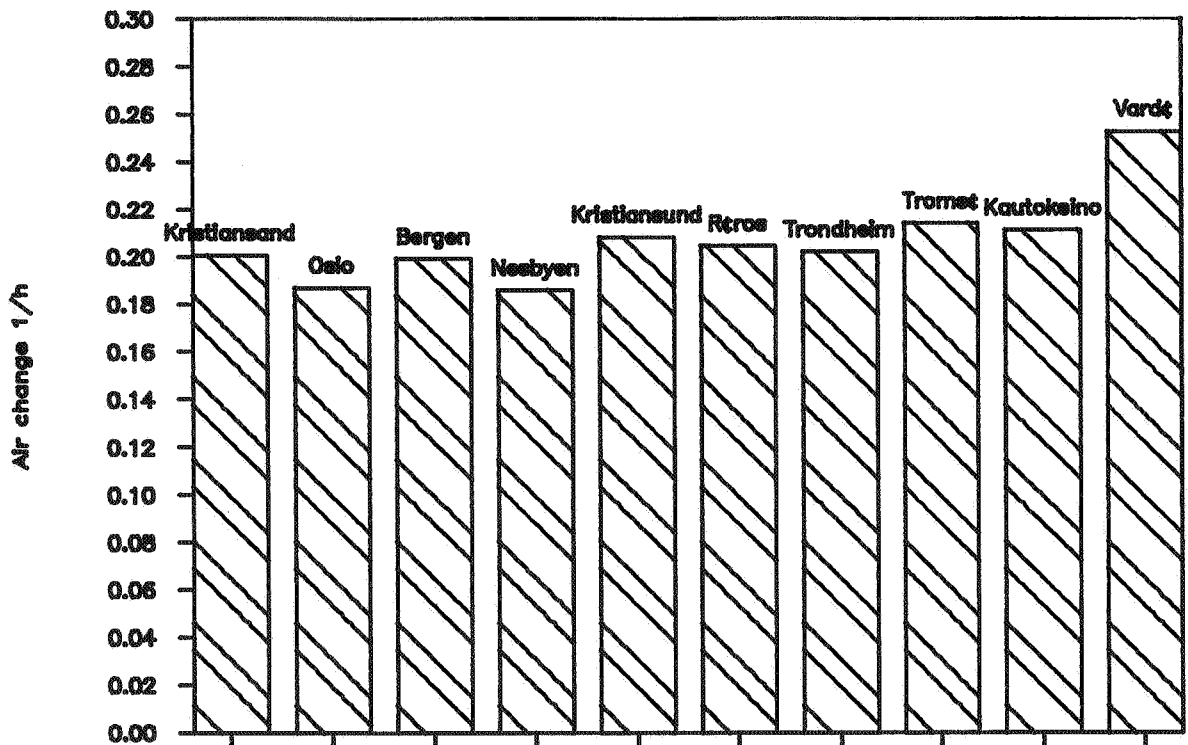


Figure 6. Yearly mean infiltration air change (1/h) for towns in Norway

hour and the standard deviation was 1,5. For the simulation in this paper it was tested if the values were normally distributed. They were. The simulation could then be made with normally distributed values.

6. SIMULATION

The simulation is done by using the ELA model and for some of the parameters used random generated values. The following parameters were each expected to have a normal distribution. The mean values and the standard deviations is given.

1. Indoor temperature
Mean value 21 C
Standard deviation 1,5 C
2. Air change at 50 Pa pressurization
based on measurements
Mean value 4,7 changes per hour
Standard deviation 1,5 changes per hour
3. Leakage part in the ceiling
Mean value 0,38
Standard deviation 0,05
4. Leakage part in the floor
Mean value 0,16
Standard deviation 0,03
5. Shielding factor
Mean value 0,28
Standard deviation 0,03
6. Extra building height
Mean value 1 m
Standard deviation 0,5 m

Most of the values were selected after discussions with other researchers at the institute. We use the spreadsheet model for the case with the 2 floor building in Oslo and calculations on monthly climate values.

To make one calculation we need 6 random generated numbers between 0 and 1. One random number for each parameter. Note that we have assumed that the 6 parameters are independent of each other. If that is not the

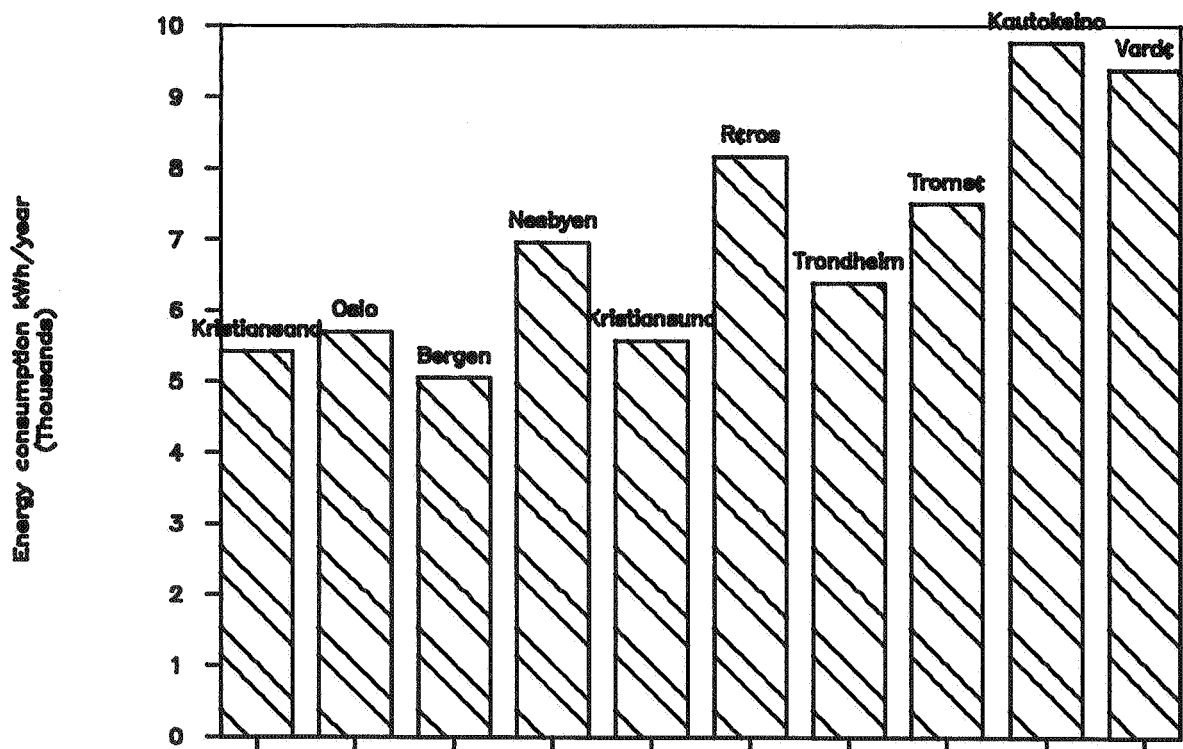


Figure 7. Yearly energy consumption (kWh) for infiltration air for towns in Norway

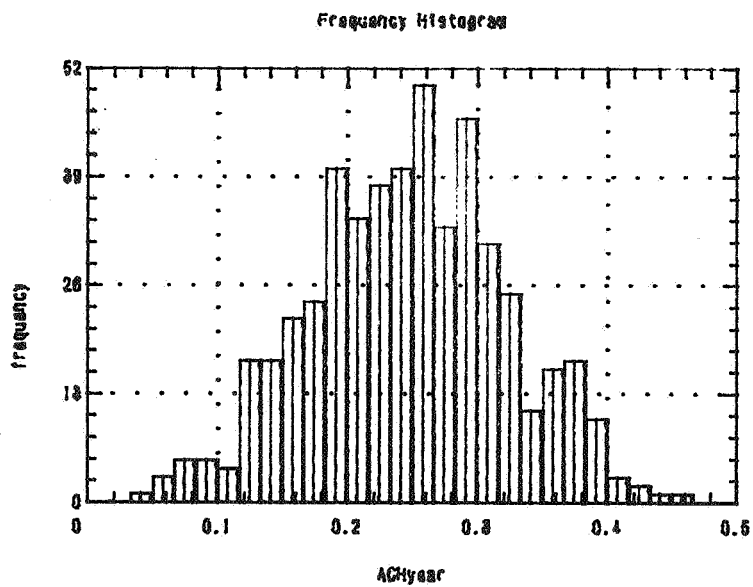


Figure 8. Histogram for 500 simulations of yearly mean air infiltration (l/h)

case, the dependence must be given. Each random number is then transformed to generate normal distribution with the given mean value and standard deviations. If we make many calculations then we will be sure to get parametric values that will follow a normal distribution. In this case we have made 500 simulations. Figure 8 gives a frequency histogram for the mean yearly air change. The mean value is 0,24 and 10% is below 0,13 and 10% is above 0,33. Figure 9 is a normal probability plot of the values from figure 8. As the values follow a straight line, they are normally distributed. A small deviation in the lower part is probably caused by a few cases being taken away. The results can also be given as a cumulative distribution curve, where it easier to find the number of cases above or below a certain value.

Figure 10 gives the frequency histogram for the energy consumption. The mean value is 7530 kWh/year and 10% is below 3600 kWh and 10% is above 10000kWh. The results show that measurements of energy consumptions typically will give from 3600 to 10000 kWh/year.

The results of the simulation can be used to find the most important parameters. In this case it is the air change at 50 Pa pressurization.

Figure 11 shows the regression line and the points for yearly air change in dependence of the 50 Pa value. The correlation described by the R^2 is 0,98 or very good. A prediction of the mean yearly air change based on the measured 50 Pa air change will therefore be very good. In figure 12 is given the residuals in the regression. The residuals is seen to increase at higher air change but not alarming.

Figure 13 gives the regression between the the yearly energy consumption and at 50 Pa air change. The variations is a little higher than the previous case but still a good prediction

Figure 14 gives a case with a very poor regression. In this case it is between the indoor air temperature and the mean yearly air change.

7. CONCLUSIONS

The statistical method with using random generated numbers is used for calculations of typical distributions in yearly infiltration air change and energy consumptions. The result is that from a knowledge of the 50 Pa leakage air change can we make good predictions of the yearly infiltration as most of the other parameters do not have high influence. These results are based on the simplified equivalent leakage model and will of course not take into account complicated cases with different wind distributions and

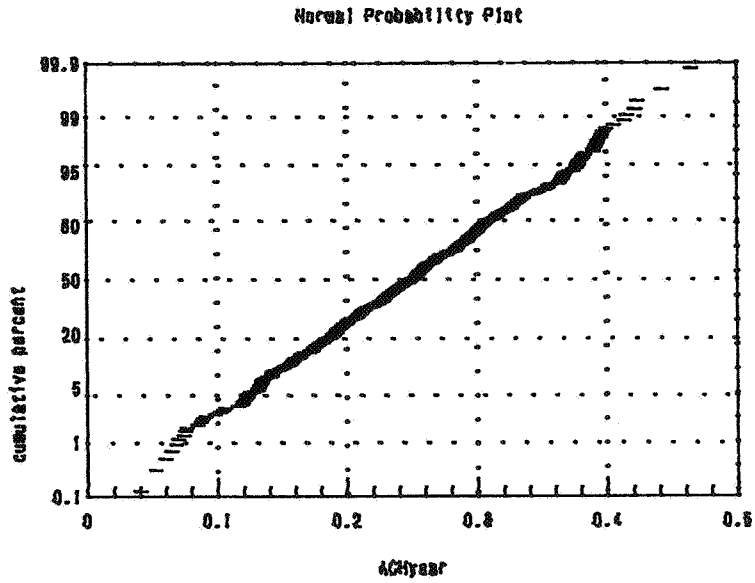


Figure 9. Probability plot for 500 simulations of yearly mean air infiltration (1/h)

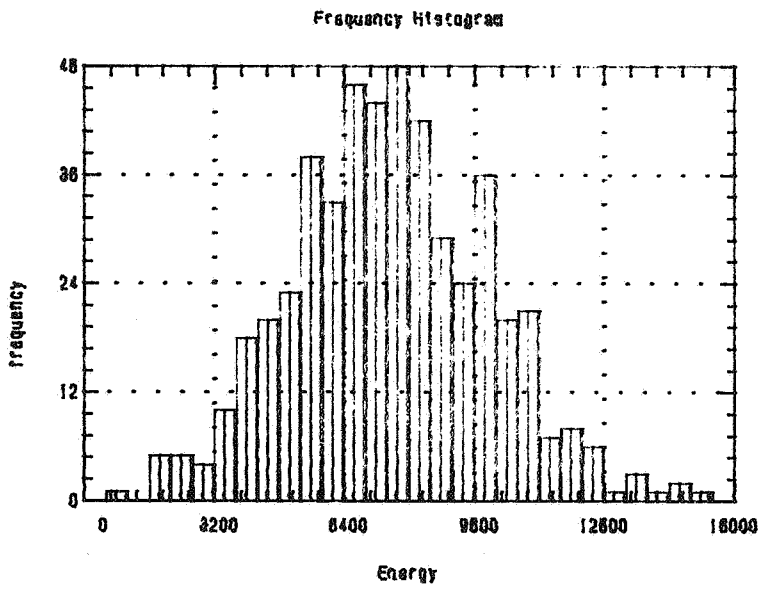


Figure 10. Histogram for 500 simulations of yearly energy consumption (kWh) for infiltration

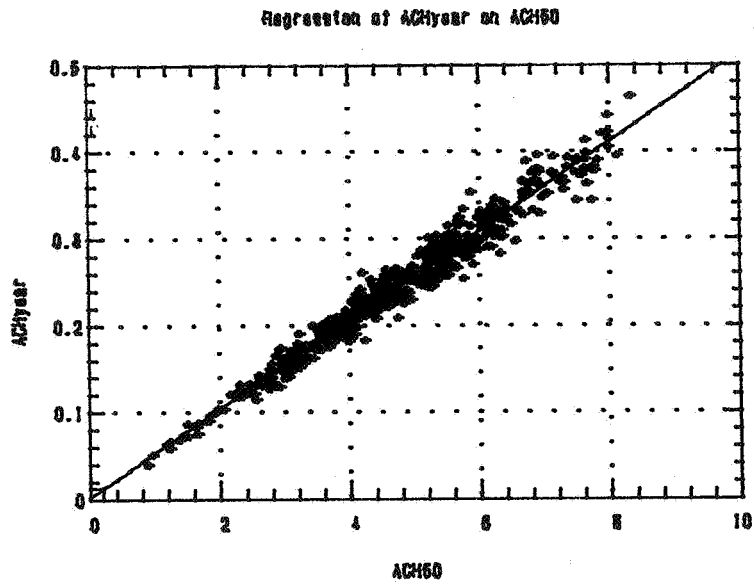


Figure 11. Regression for 500 simulations of air infiltration. Mean yearly air change versus 50 Pa pressurization air change. Regression line is plotted

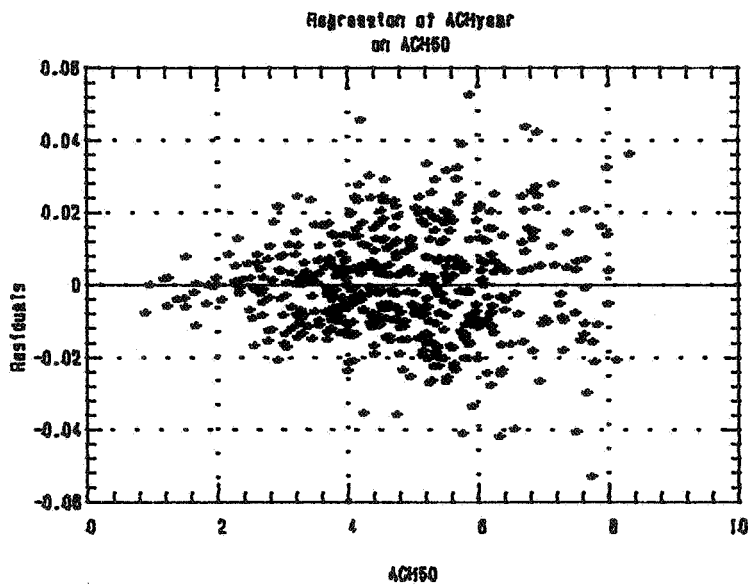


Figure 12. Residuals from the model in figure 11

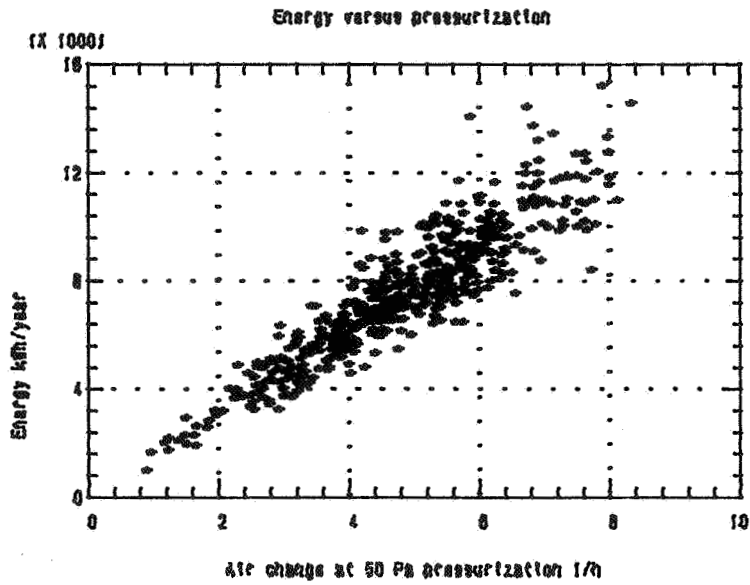


Figure 13. Regression for 500 simulations of air infiltration. Yearly energy consumption versus 50 Pa pressurization air change

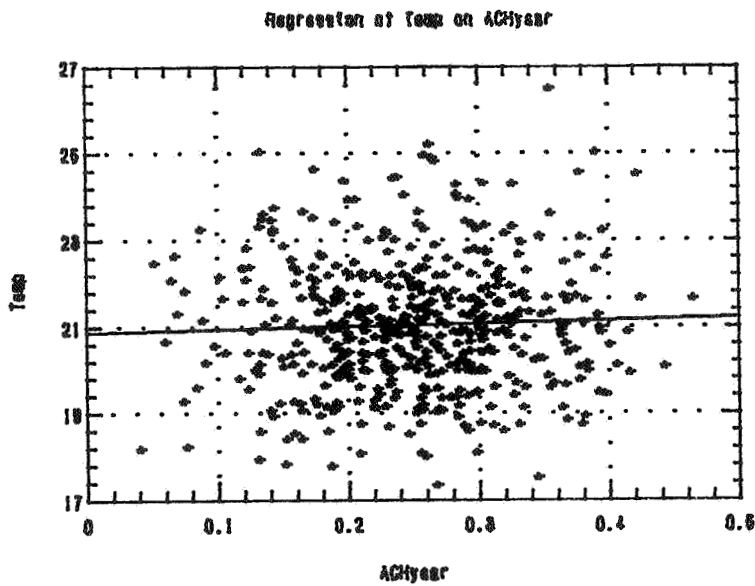


Figure 14. Regression for 500 simulations of air infiltration. Indoor temperature versus yearly mean air change

more rooms in the building. But the simulation method can be used on very complicated models to find out which parameters are important as it is highly unlikely that all values are in the extreme at the same time.

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PAPER 10

THERMAL COUPLING OF LEAKAGE FLOWS
AND HEATING LOAD OF BUILDINGS

R. KOHONEN, T. OJANEN AND M. VIRTANEN

Laboratory of Heating and Ventilating
Technical Research Centre of Finland
Lampomiehenkuja 3
SF-02150 Espoo 15
Finland

SYNOPSIS

The actual heating load of a building differs often from the designed load. One reason for this is the uncontrolled ventilation through a building envelope. The heating load of air infiltration has, in practical calculations, been calculated according to the predicted leakage flow rate and to the indoor and outdoor air temperature difference.

We suggest, however, that the value of transmission heat losses should be corrected by a factor, Nusselt number, because of the thermal interaction of leakage flows and conduction heat transfer in wall structures. According to computer simulations and experiments, the warming up of leakage flow may be as high as 90 % of the indoor and outdoor air temperature difference. Correspondingly, the Nusselt numbers describing the mean relative reduction of transmission heat losses can be 0,65. The seasonal heating energy savings are of the order of 10 - 15 %.

The thermal interaction of leakage flows and wall structures was analyzed by computer simulation and experiments with some elementary flow cases in typical wall structures. The results are, however, so obvious that some theoretical and practical conclusions could be made.

NOMENCLATURE

A	= area, m ²
C	= capacity flow rate, W/K
C'''	= volumetric heat capacity, J/m ³ K
c _p	= specific heat capacity, J/kgK
d	= thickness, m
d _h	= hydraulic diameter, m
g	= gravity force, = 9,81 m ² /s
h	= specific entalpy, J/kgK height, m
K _v	= permeability, m ²
k	= thermal transmittance, W/m ² K
L	= length, m
Nu	= Nusselt number, defined in text
n	= unit normal vector
p	= static pressure, Pa
q	= heat flux, W/m ²
q _m	= mass flow rate, kg/s
q _v	= volume flow rate, m ³ /s
Ra*	= modified Rayleigh number, defined in text
Re	= Reynolds number, = vd _h /ν
T	= temperature, K or °C
t	= time, s
v	= velocity, m/s
Y	= response factor, W/m ² K
α	= convective heat transfer coefficient, W/m ₂ K
β	= thermal expansion coefficient, 1/K
ε	= response factor
η	= viscosity, kg/ms
λ	= thermal conductivity, W/mK
ρ	= density, kg/m ³

1. INTRODUCTION

The actual heating load of a building often differs from the designed load. One reason for this is the uncontrolled ventilation through a building envelope. Hydraulic properties of different leakage routes have been studied widely, and leakage flow rates can nowadays be predicted rather well. The thermal coupling of leakage flows and heating load has not, however, been studied, and, therefore, the heating load of leakage ventilation has been calculated assuming that the leakage air flows in at the outside temperature. The thermal coupling of leakage flows and transmission heat flow should be considered in simulation of dynamics of room spaces as well.

In heat balance considerations we should be aware of the control surface of the system, for which the heat balance is formed, is located. In steady-state considerations, it is reasonable to consider the outer surface of a structure as the control surface. Thus, the transmission heat flow is less in the case of infiltration flow compared with pure conduction and the inlet temperature (inflow temperature at the control surface) of infiltration air is equal to the outdoor air temperature. In the case of exfiltration the transmission heat flow is higher than in the case of pure conduction and the outlet temperature is less than indoor air temperature. The heat recovery effect of leakage air is approximately the same for both infiltration and exfiltration. The difference arises only from the nonlinearities of the system. In nonsteady-state heat balance considerations, it is, however, preferable to set the control surface at the inner surface of wall structures, i.e., the heat balance is formed for the indoor air. This approach enables us to use the ordinary simulation programs for energy analysis of buildings with minor changes. Exterior walls should be divided into sections where pure conductive or combined convective and conductive heat transfer occurs. In the case, there are two- or three-dimensional flow cases, two- or three-dimensional response factors, transfer functions, finite difference approaches, etc, should be used correspondingly.

In this paper the thermal influences of leakage flows are considered at two levels:

1. At the building component level, the thermal effect (heat recovery) of typical leakage flows will be considered. The types of leakage flows are crack flow, pure infiltration and combined infiltration and crack flow. The interaction of airflows and heat transfer in structures is analyzed both in steady-state and dynamic conditions by computer simulation using the finite difference approach. Some results of experiments will also be shown.
2. At the building (envelope) level, the correlation between airtightness, air change rates, and thermal performance will be considered. A multi-cell approach will be applied

in the calculation of leakage rates, while the thermal coupling of leakage flow and conductive heat transfer is based on two-dimensional transfer function and finite difference approaches. Some results of experiments will also be shown.

2. HEAT BALANCE OF A BUILDING

2.1 Heating load of leakage flows and transmission losses

Our preliminary calculations (Kohonen et al.) showed that warming up of leakage air is rather efficient on leakage routes. With allowable leakage flow rates in relation to thermal comfort (0,5 - 0,7 dm³ /sm), the heating is 25 - 60 % of the outside and inside temperature difference, corresponding to Nusselt's numbers 0,9 - 0,7. Based on this fact, we suggested the heating load of infiltration, exfiltration and transmission be calculated according to Eq. 1 (see Fig. 1)

$$\phi = (-\sum_i q_{m,i} T_o + \sum_e q_{m,e} T_e + (\sum_i q_{m,i} - \sum_e q_{m,e}) T) c_p + \sum_k Nu_k \cdot \bar{k}_k \cdot A_k \cdot (T - T_o) \quad (1)$$

where subscripts i, e, and o denote infiltration, exfiltration, and outdoor temperature, respectively. T is the indoor temperature and k the overall average thermal transmittance (k-value) of a structure. The Nusselt numbers Nu_k take into account the thermal effect of leakage flows (infiltration/exfiltration) as well as internal convection flows of structures. In a case of pure conduction the Nu-number is equal to 1. The Nusselt number is defined by Eq. 2 (see Fig. 2)

$$Nu = \frac{\int q d\Gamma}{\int q_o d\Gamma} \quad (2)$$

where q and q_o denote the heat fluxes on the control surface (a wall section) with and without convection or leakage flows, respectively.

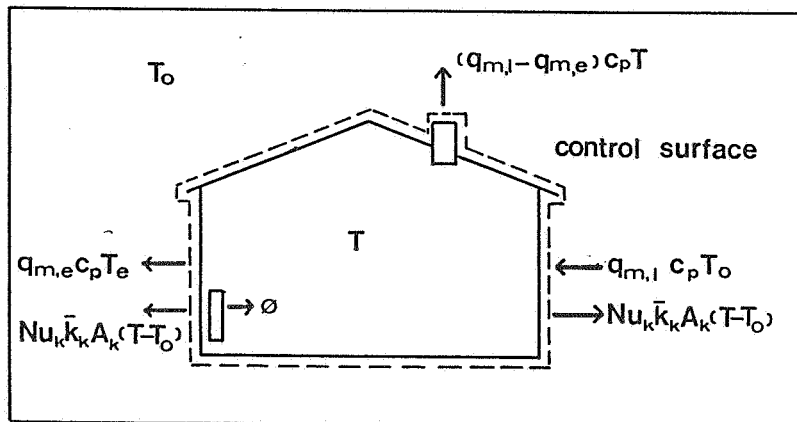


Figure 1. Heat balance of a building

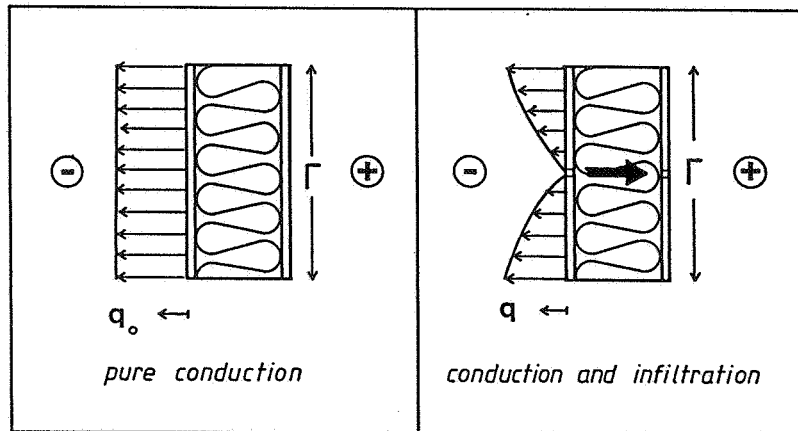


Figure 2. Nusselt-number definition.

For practical calculations, Nusselt numbers for different leakage (ex-/infiltration) cases should be determined. In the following experiments in VTT's test houses, in an existing building and in laboratory as well computer simulation will be described in order to introduce some practical value, for Nu_k :s.

2.2 Experiments

Measurements concerning the thermal effects of leakage flows have been done in test houses, in laboratory and in the field. In a test house controlled conditions were created, so that it was exactly known where and how much air flows in through building envelope. The test house was provided with an exhaust ventilating system and the wall sections were separated from each other with convection cuts. Thus, the internal convection flows from one wall to another were eliminated.

In Fig. 3 are shown the measured, and also calculated steady-state results for one wall section. The outside temperature is $4.5\text{ }^{\circ}\text{C}$ and inside temperature is $21.0\text{ }^{\circ}\text{C}$, respectively. The measured pressure difference over the wall was 27 Pa. The inside surface is absolutely airtight, except one crack through which the air flows in. The measured air flow rate was $q_v = 0.87\text{ l/sm}$. The air flow field, shown in Fig. 3, is calculated. Also the temperature isotherms are calculated. We can see that there is a good agreement with measured and calculated temperatures.

The according to Eq. 2 calculated mean Nusselt number, for the whole wall section, is in this case $Nu = 0.13$. The temperature of incoming air is $13.7\text{ }^{\circ}\text{C}$. As it can be seen from Fig. 3, the temperature gradient is relatively strong near the inflow point. If the temperature of incoming air is $10\text{ }^{\circ}\text{C}$, the mean Nu -number would be 0,70.

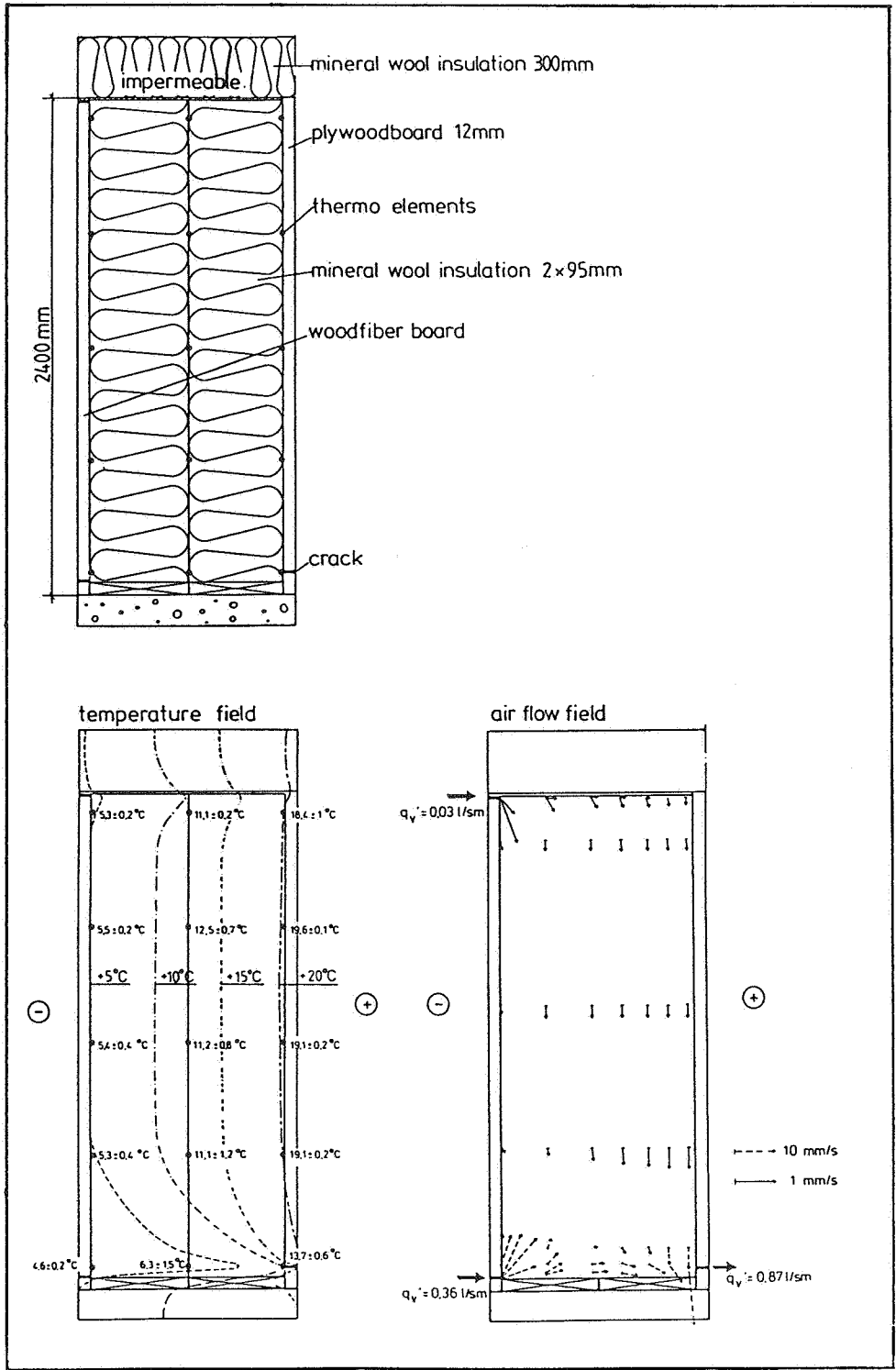


Figure 3. Measured and calculated temperature and air flow field

The mean Nusselt number was determined also for the whole building (test house). The supply air came in through several leakage routes in a building envelope. The total air change rate was $n = 2.4$ 1/h and the corresponding mean Nusselt number was $Nu = 0.67$ ^{+0.17} _{-0.10}.

In Fig. 4 is shown the measured and calculated heating of leakage air in a crack as well as the heat flux profiles of inside surface. The measurements have been done in laboratory conditions. The outside temperature was -12.8 °C and inside temperature was 22.7 °C, respectively. The measured airflow rate was $q_v = 2.7$ l/sm and the mean Nusselt number was for the wall $Nu = 0,45$.

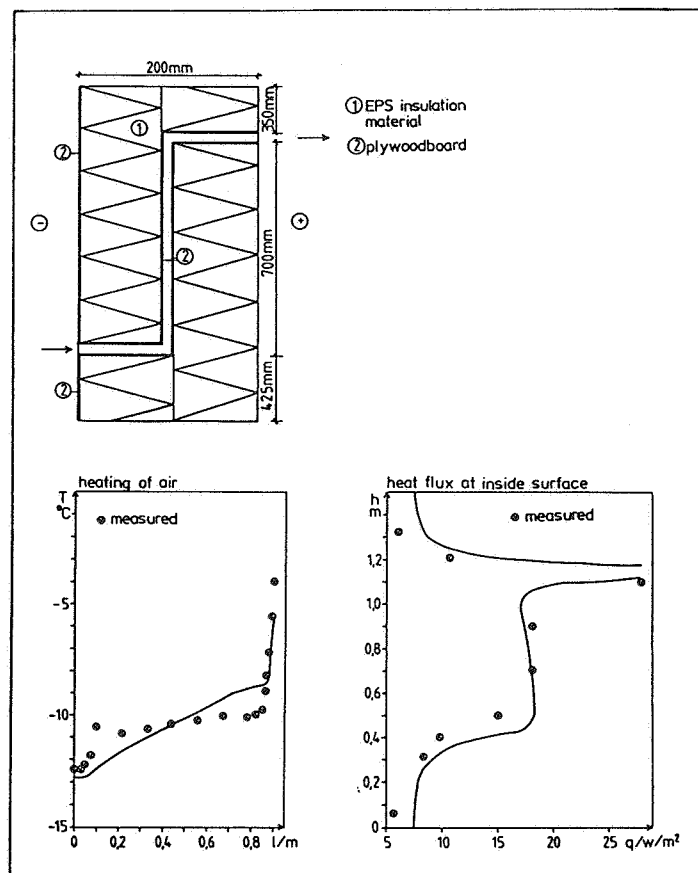


Figure 4. Measured and calculated heating of leakage air in a crack ($h = 10$ mm), and the heat flux profiles of inside surface.

Let us consider the significance of the warming of the leakage air with example from an existing building. Our example building is a day nursery whose building volume is 2700 m³. The building is provided with an exhaust ventilating system. The measured airtightness of the building envelope was $n_{5,0} = 3.2$ 1/h. The main leakage routes were packing leakages of windows and doors. The leakages were analyzed by smoke tests

and IR-camera tests. The heating load of the building was determined by calculation and measurements. The thermal transmittance representing the transmission heat losses was according to calculations 820 W/K. The capacity flow rate of the exhaust air was (according to measurements) 1370 W/K. The mean underpressure of the inside air was 12 Pa. Thus the measured air flow rate represents the total ventilation. The mean inside temperature was 20 °C. Fig. 5 shows the measured and calculated heating loads of the building as a function of the outdoor temperature. We find that $Nu = 0.8$ gives the measured heating load.

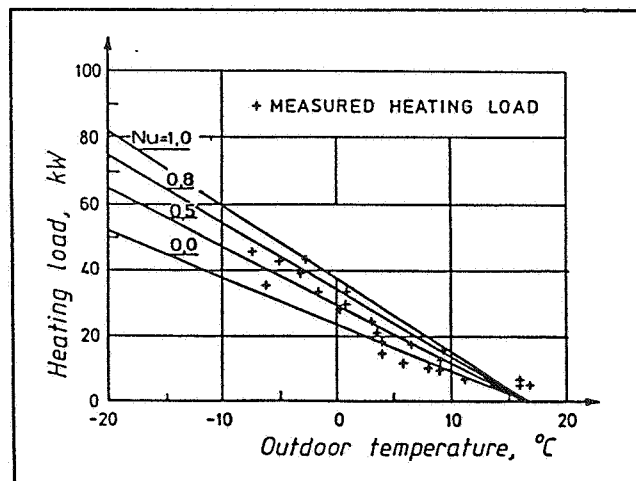


Figure 5. The measured and calculated heating load of building.

2.3 Computer simulations

When evaluating the effect of leakage flows on the heating load of a building in a dynamic condition, the heat balance and the airflow balance have to be solved simultaneously.

We are now considering a building that is supplied with an exhaust ventilating system (Kohonen & Virtanen). The total air change rate is assumed to be constant, $n = 0.5$ l/h. The inside temperature is also constant, $T_i = +20$ °C (ideal control system). The airtightness of the building envelope is $n_{50} = 3.0$ l/h.

The supply air flows in through a crack that is equal over the building perimeter (Fig. 6). Two simplified cases will be considered: a short crack and a long crack. In both cases the dependency of leakage flow rate and the pressure difference between the outside and inside air is the same.

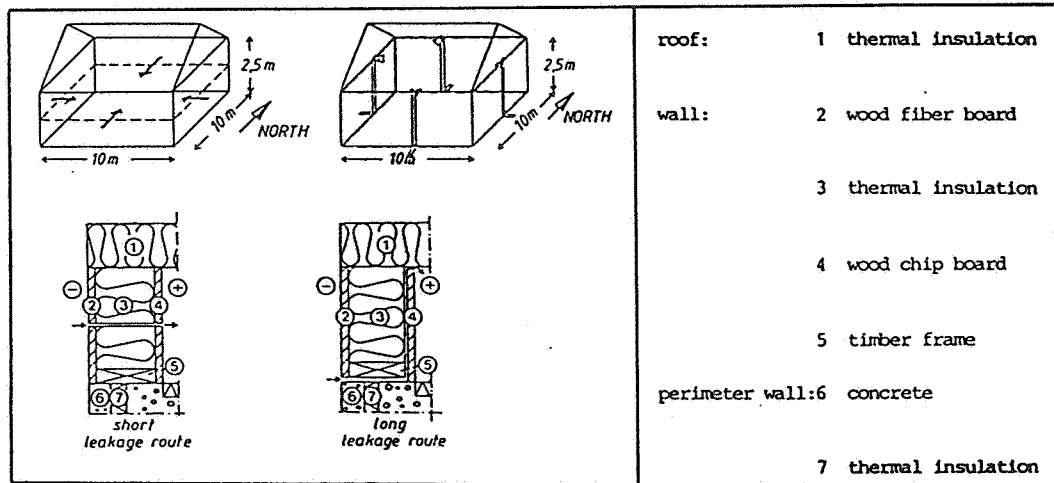


Figure 6. The leakage routes of the example building

The heat balance of the building is calculated with both the two-dimensional finite-difference method and the transfer function approach with one hour time steps. The heating load calculation was done for a two-week period. The weather data of the period is shown in Fig. 7. The wind direction 0° refers to north.

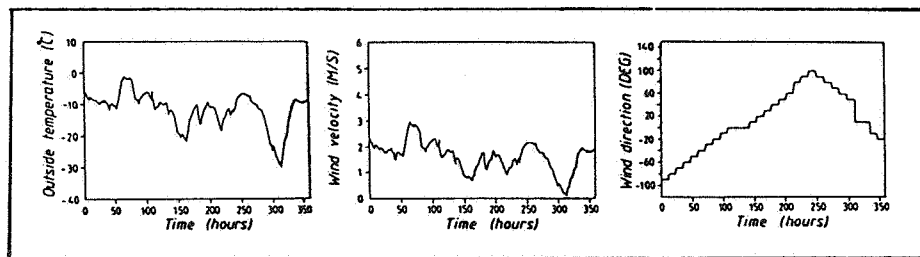


Figure 7. The weather data of the calculation period.

The heating load of conduction and ventilation and the total heating load in a case of a short crack over the building perimeter are shown in Fig. 8. The mean Nusselt number for the period (representing the whole building envelope) is 0.73 and the reduction of total energy for the period when the heat recovery is taken into account is 12.3%. There is a good agreement with the results calculated with the finite-difference and with response factors.

The heating load components for the long leakage route are shown in Fig. 9. It seems that the heating load of conduction calculated with response factors is too optimistic. The according to finite-difference method calculated mean Nu-number for the period is 0.65 and the reduction of total energy is 15.2%.

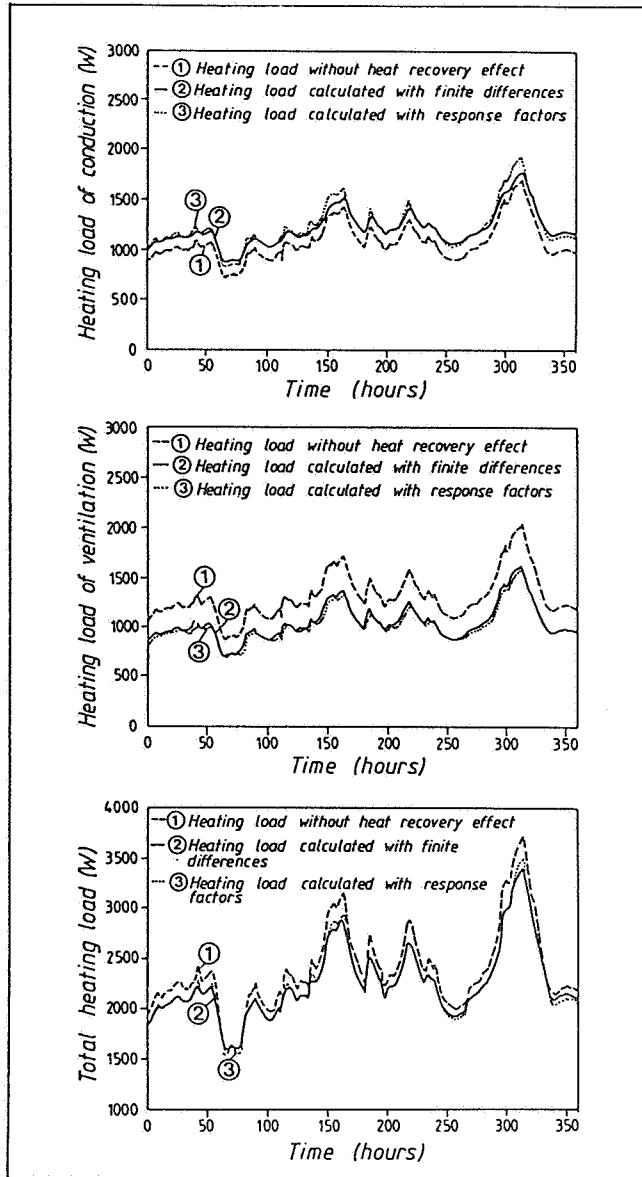


Figure 8. The heating load of conduction and ventilation as well as the total heating load of building in the case of a short crack.

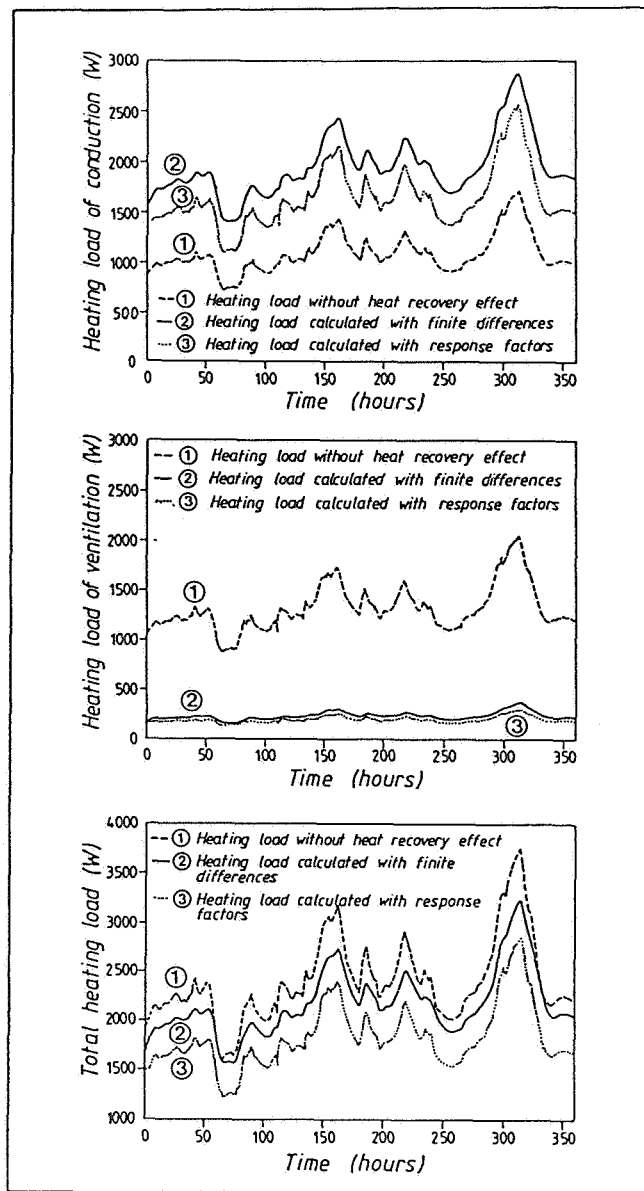


Figure 9. The heating load of conduction and ventilation as well as the total heating load of building in the case of long crack.

3. INFLUENCES OF LEAKAGE FLOW ON THERMAL PERFORMANCE OF A STRUCTURE

3.1 Elementary flow cases

In general, the types of leakage flows are crack flow, crack flow and infiltration, and pure infiltration.

In the case of pure filtration, the continuity, momentum and energy equations are (Kohonen, R et al.):

$$\frac{\partial}{\partial t} \langle \rho_f \rangle = -\nabla \cdot \langle \vec{q}_{m,f} \rangle \quad (3)$$

$$\frac{\partial}{\partial t} \langle \rho_f \vec{v}_f \rangle = \frac{K_{v,f}}{\eta_f} \cdot (\nabla^2 \langle p_f \rangle^{(f)} + \beta \langle \rho_{f,ref} \rangle^{(f)} \vec{g} \cdot \nabla \langle T \rangle) \quad (4)$$

$$\frac{\partial}{\partial t} \sum_{\alpha=s,f} \langle \rho_\alpha h_\alpha \rangle = -\nabla \cdot \sum_{\alpha=s,f} \langle \vec{q}_\alpha \rangle - \nabla \cdot \langle h_f \vec{q}_{m,f} \rangle \quad (5)$$

When deriving the momentum equation, we have assumed that the airflow is a Darcy-type flow; the density of air is a function of temperature and the air behaves as ideal gas; the air and the solid matrix (wall structure) have equal temperatures locally; and the body force (f) may be replaced by gravity force (g). In building physics applications, the capacity terms in Eqs 3 and 4 can be assumed zero.

In a building structure, there may occur internal convection although there are no cracks through it.

Fig. 10 shows the Nusselt number as a function of the modified Rayleigh number, Ra, for closed and at the cold surface open cavities (Kohonen and Ojanen).

As we can see in Fig. 10 convection has only a slight influence on the mean heat flux. In experiments (Nu may be as high as 1.2 with $Ra^* = 5$ and $h/d = 7$) we found, however, that the excess of transmission heat transfer is significantly greater owing to non-ideal filling of the test cavities.

A more detailed analysis of the influences of natural convection on transmission heat losses is given by Kohonen et al.

In the case of crack flow, the energy equation of the flowing component can be written in the form

$$\frac{\partial}{\partial t} \langle \rho_f h_f \rangle = -\nabla \cdot \langle \vec{q}_f \rangle - \nabla \cdot \langle h_f \vec{q}_{m,f} \rangle - \frac{1}{V} \int_{\partial V_{fs}} \vec{q}_f \cdot \vec{n}_{fs} dA \quad (6)$$

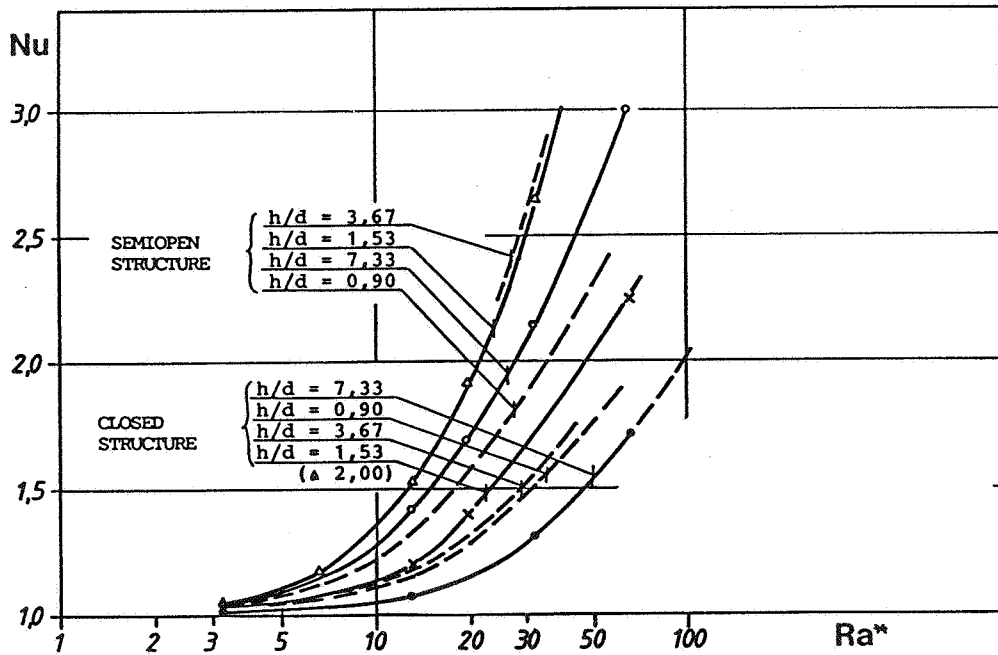


Figure 10. Nusselt number for closed and at the cold surface open cavities (Kohonen & Ojanen).

Correspondingly, for the stagnant component, s,

$$\frac{\partial}{\partial t} \langle \rho_s h_s \rangle = -\nabla \cdot \langle \vec{q}_s \rangle - \frac{1}{V} \int_{\partial V_{sf}} \vec{q}_s \cdot \vec{n}_{sf} dA. \quad (7)$$

The thermal coupling between the components s and f can be given by Eg. 8

$$\int_{\partial V_{sf}} \vec{q}_s \cdot \vec{n}_{sf} dA = \int_{\partial V_{sf}} \alpha_{sf} (T_s - T_f) \cdot \vec{n}_{sf} dA. \quad (8)$$

Fig. 11 shows the heating of leakage air as a function of the length of leakage route, heat flux profiles at the outer surface, and the Nusselt numbers with different leakage flow rates on some typical leakage routes. The calculations have been carried out for steady-state conditions where the outside and inside temperatures are -10°C and $+20^\circ\text{C}$, respectively.

The outer surface of the structure is cooled as the leakage air in outside temperature flows into the crack and is heated there by the conduction heat flow. As a result, the heat flux at the outer surface is decreased (constant heat transfer coefficient at surface). Heat losses at the outer surface decrease more effectively the higher leakage flow rates are. In Fig. 11 the heat flux profiles drawn with a solid line represent pure conduction. The dashlines take the effect of leakage flow into account. The area between solid lines and

dashlines represent the heat recovery effect of the leakage flow. The Nusselt numbers have been calculated by integrating the heat flux over the wall section where there are changes due to leakage flow (determined according to the highest considered leakage flow rate), and by taking Eq. 2 into account.

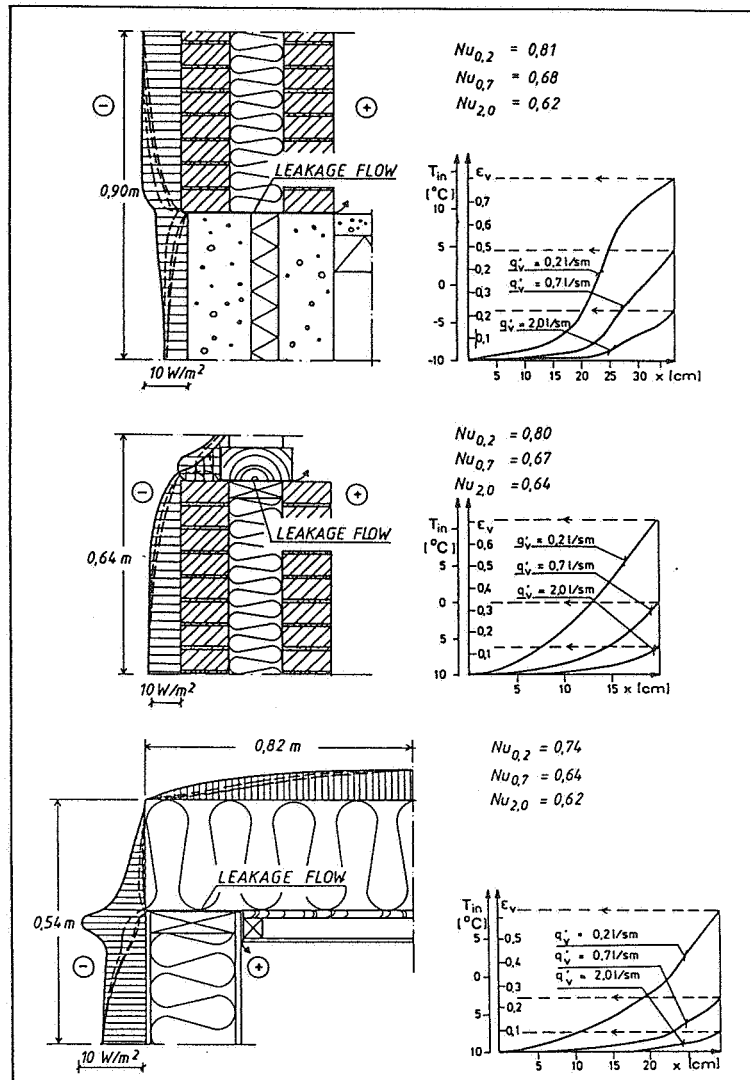


Figure 11. Warming up of leakage flow and Nusselt numbers for some typical flow wall structures.

Let us consider the thermal effect of airflow in the wall structure shown in Fig. 12. In our steady-state example, the air flows in first by pure infiltration. The leakage flow rate is $q_v = 0.1 \text{ dm}_3/\text{s}/\text{crack m}$.

The mean heat flux of the outside surface, which represents conduction heat losses, would be for pure conduction $q_{c,0} = 4.7 \text{ W/m}^2$ (thermal coupling not considered). If the heat

recovery effect is taken into account, the corresponding heat flux is $q_c = 4.33 \text{ W/m}^2$ and the air flows in at $17.7 \text{ }^\circ\text{C}$ temperature. The Nusselt number calculated according to Eq. 2, representing the heat recovery effect, is now $Nu = 0.92$.

If we assume that the same airflow rate comes in by pure crack flow through a crack whose height is $h = 5 \text{ mm}$, the thermal effect is exactly the same as by pure infiltration. If the height of the crack is $h = 2.5, 25, \text{ or even } 50 \text{ mm}$, the mean heat flux at the outside surface would be, correspondingly, $q_c = 4.14, 4.38, \text{ and } 4.43 \text{ W/m}^2$; the temperature of incoming air would be $T_{i_n} = 17.3, 18.3 \text{ and } 18.5 \text{ }^\circ\text{C}$; and, finally, the Nu-number would be $Nu = 0.88, 0.93 \text{ and } 0.94$, respectively. It can be concluded that the connection between the flowing air and the wall structure, i.e., the importance of the convective heat transfer coefficient in a crack, is rather weak. More important is the length of the leakage route.

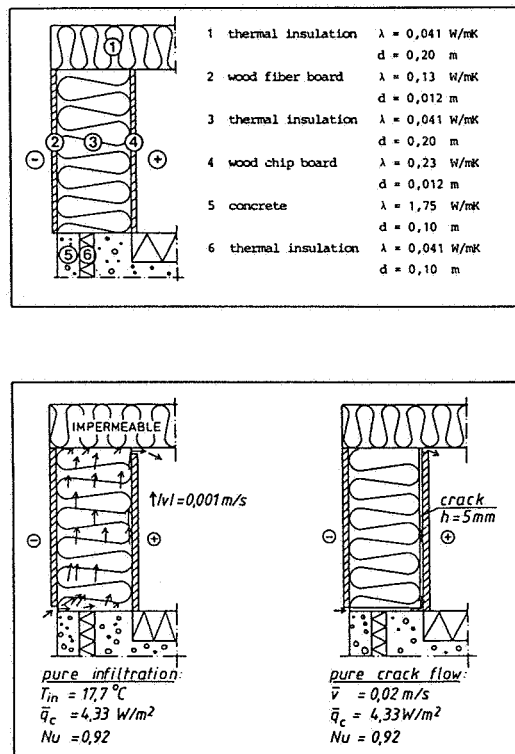


Figure 12. Thermal effect of air flow in a wall structure by pure infiltration and by pure crack flow.

We also studied the heat recovery effect on the total heat losses assuming that there was always the same airflow rate between inside and outside air spaces. Without any heat recovery, the convective heat losses are $q_m \cdot c_p \cdot (T_i - T_o)$. In the case of air infiltration through the structure, the heat recovery will reduce the convective heat losses to be

$q_m * c_p * (T_i - T_{i,s})$ at the inside control surface, where $T_{i,s}$ is the temperature of incoming air. Thus the convective heat losses are reduced but the heat conduction at the inside surface will increase.

The relative change of total heat losses are presented with a modified Nusselt number, which in the case of infiltration is

$$Nu^* = \frac{\int_{\Gamma} q_c d\Gamma + q'_m c_p (T_i - T_{i,s})}{\int_{\Gamma} q_{c,o} d\Gamma + q'_m c_p (T_i - T_o)} \quad (9)$$

where q_c and $q_{c,o}$ are conductive heat flows through the control surface in convection and pure conduction conditions, respectively. The definition of Nu-number is suitable for, for instance, optimizing calculations of so called dynamic insulation, while with Eq. 2 defined Nu-number is more practical in heat demand calculations.

Fig. 13 shows the modified Nusselt number as a function of flow rate (Ojanen) for infiltration and exfiltration. As we can see in Fig. 13, there is an optimal flow rate, with which the total heating load is at minimum. The optimal flow rate depends, of course, on the wall structure. In the case of Fig. 13 the structure had 300 mm thick mineral wool insulation and 12 mm woodfiber board and woodchip board covers at cold and warm surfaces, respectively.

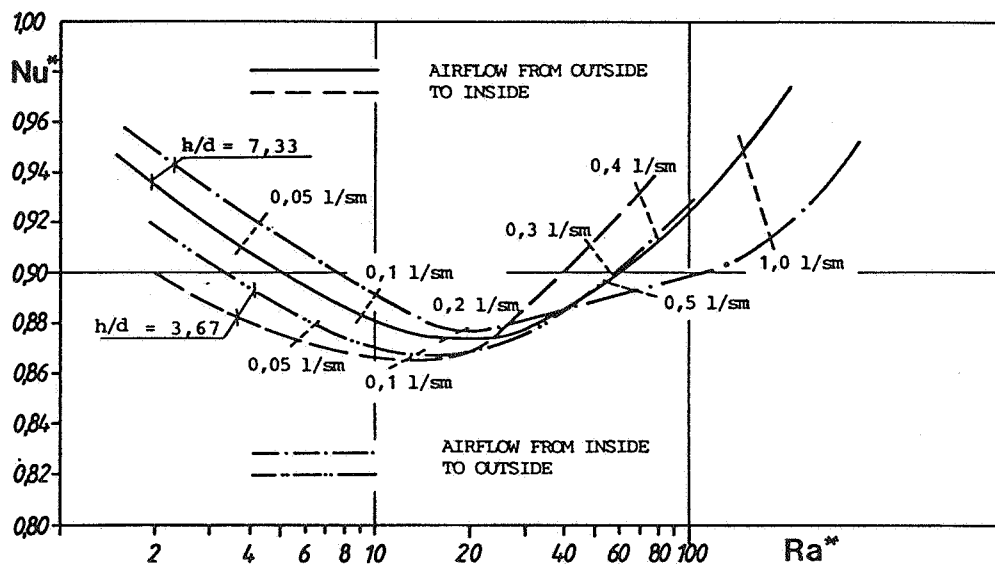


Figure 13. Modified Nusselt number vs modified Rayleigh number for ex- and infiltration flows in a wall structure (Ojanen).

We can see also that the Nusselt number is the same for in- and exfiltration. Only non-linearities of the thermal system may cause differences between ex- and infiltration. This holds, however, for steady-state conditions.

3.2 Dynamic behavior of leaky wall structures

The thermodynamic behavior of wall structure is also influenced by leakage flows. This is commonly omitted, i.e. leakage flows are considered as a passive element in relation to heat transfer due to transmission. In energy analysis programs two approaches are commonly used when calculating transmission heat transfer in wall structures with thermal capacity: transfer function and finite difference methods.

When using the transfer function approach, the mean heat flux at inside surface for each facade and roof (representing conductive heat losses) can be calculated according to Eq. 10.

$$\bar{q}_{C,n} = \sum_{j=0}^6 Y_{j,n-j} \Delta T_{O,n-j} + R \cdot \bar{q}_{C,n-1}, \quad (10)$$

where

$Y_{j,n-j}$ is the response factor for heat flux at the inside surface,

R is the common ration.

The mean convective heat load is, correspondingly

$$A \bar{q}_{V,n} = \sum_{j=0}^6 \epsilon_{j,n-j} \dot{C}_{v,n-j} \Delta T_{O,n-j}, \quad (11)$$

where

A is the area of a wall section,

$\epsilon_{j,n-j}$ is the response factor for the temperature of incoming air,

$\dot{C}_{v,n-j}$ is the capacity flow rate of the leakage air

The variation of leakage flow rates makes the calculation of the temperature field of the structure nonlinear. Therefore, the airflow rate has to be kept as a parameter, i.e., the response factors are time-dependent. Response factors corresponding to other leakage flow rates than the parameter values are obtained by linear interpolation. In Fig. 14 some of the response factors used in a dynamic calculation in Chapter 2.3 are shown.

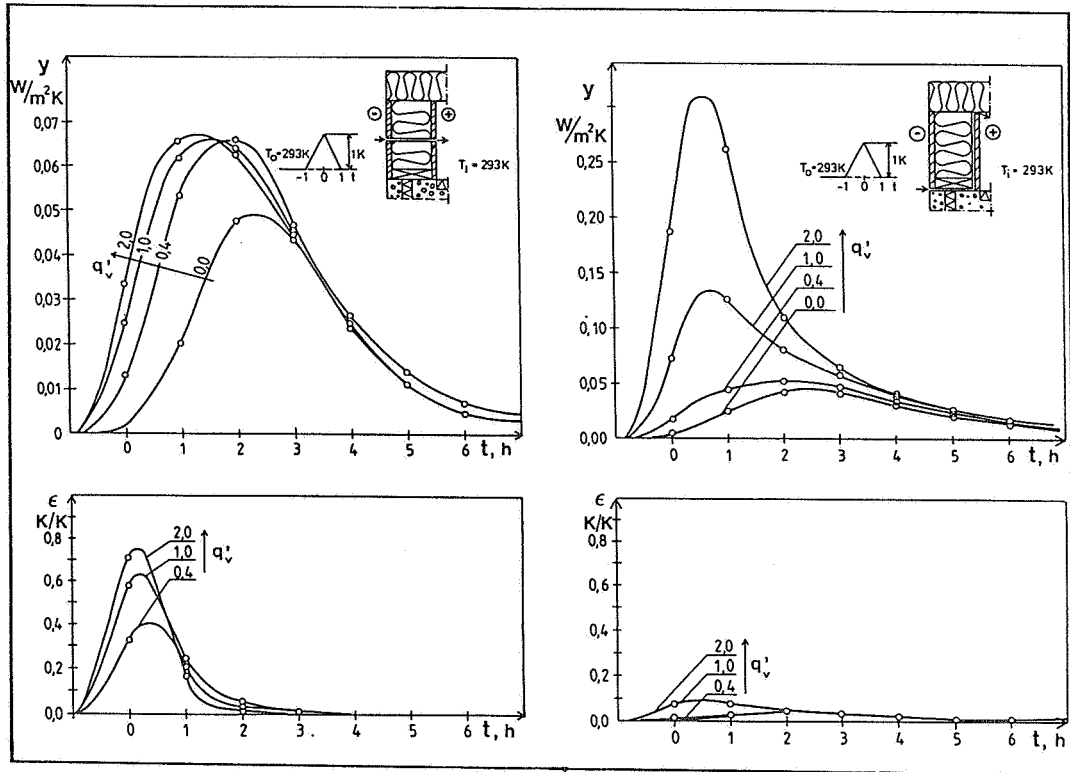


Figure 14. Response factors

It can be seen from Fig. 14 that there is the possibility that the peak values of conduction heat loss responses are taken rather purely into account. Also the linear interpolation may cause inaccuracy. Thus, it can be concluded that response factor approach is accurate only case by case.

The effect of triangular shaped outside temperature change (from $+20^\circ C$ to $+21^\circ C$ and back to $+20^\circ C$ in 2 hours) on a macro-porous structure in constant initial temperature ($+20^\circ C$) was analyzed numerically. Fig. 15 shows the calculated flow and temperature fields in the structure at different moments beginning from the first change of boundary values. Insulation thickness is 0.20 m, and inside and outside surfaces are impermeable. As the temperature raised at the other side of the structure, natural convection formed a loop in the thermal insulation. The effect of convection could be seen only in limited areas near the horizontal surfaces. In about seven hours the flow field had two convection loops due to the slightly higher temperature values in the middle of the structure.

Thus, in the case of convection the problem is not linear but dependent of temperature.

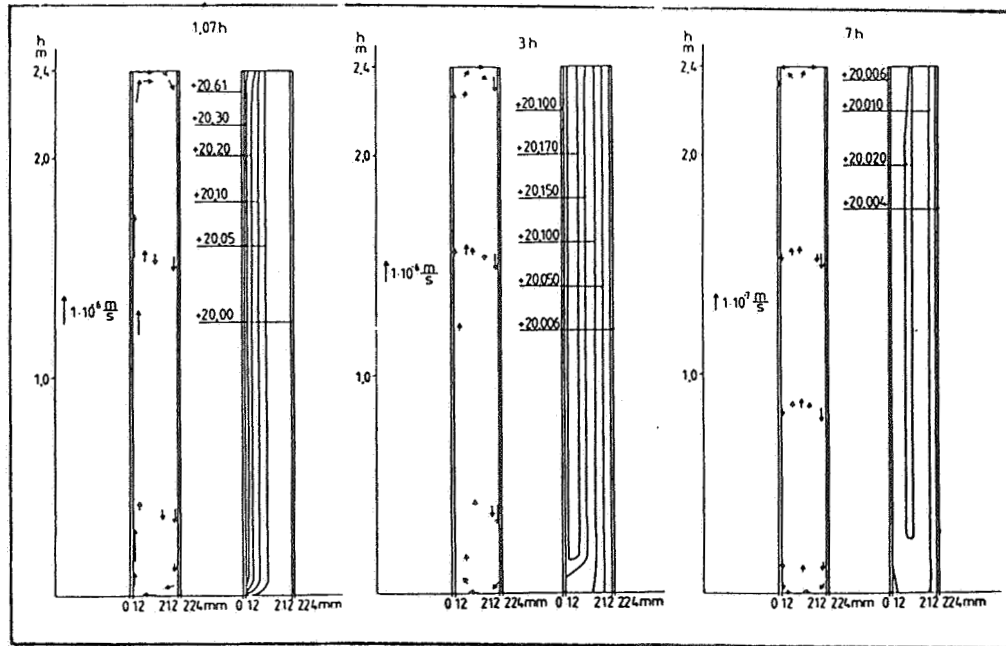


Figure 15. Temperature and air flow field as the outside temperature is changed.

3.3 Intentional exploitation of transmission losses - dynamic insulation

The profit of using intentional infiltration through wall structures (dynamic insulation) in ventilation is based on preheating the incoming air with conduction heat losses of a wall. Since the outside air is taken in through a permeable structure the rest of the building envelope should be as tight as possible. In addition, the interior underpressure should be prevailing and the effects of wind should be eliminated. The best conditions for using the counter flow wall are in a building provided with exhaust ventilation system.

In the following we shall consider with calculations the warming up of diffusively infiltrating air. The air is heated by exploiting conduction heat losses and solar energy. The calculations should be considered very preliminary. Calculations were carried out for three different wall structures (Fig. 16). The outside temperature and the solar radiation are time dependent according to the weather data of the so called reference year (Luonetjarvi). The room air temperature is assumed to be constant, +20°C. In our particular examples the outer cover board is transparent (α is the absorption coefficient of the outer surface of the structure).

In Fig. 17 the temperature of incoming air for different structures, the outside temperature and the heat flux of solar radiation for a three day period are shown.

The minimum temperature of the incoming air was set to be +10°C (with the nominal mass flow rate). If the outside temperature is lower than -10°C then the air flow rate is a half of the nominal value. The heat transfer between the cover boards and the porous body was omitted.

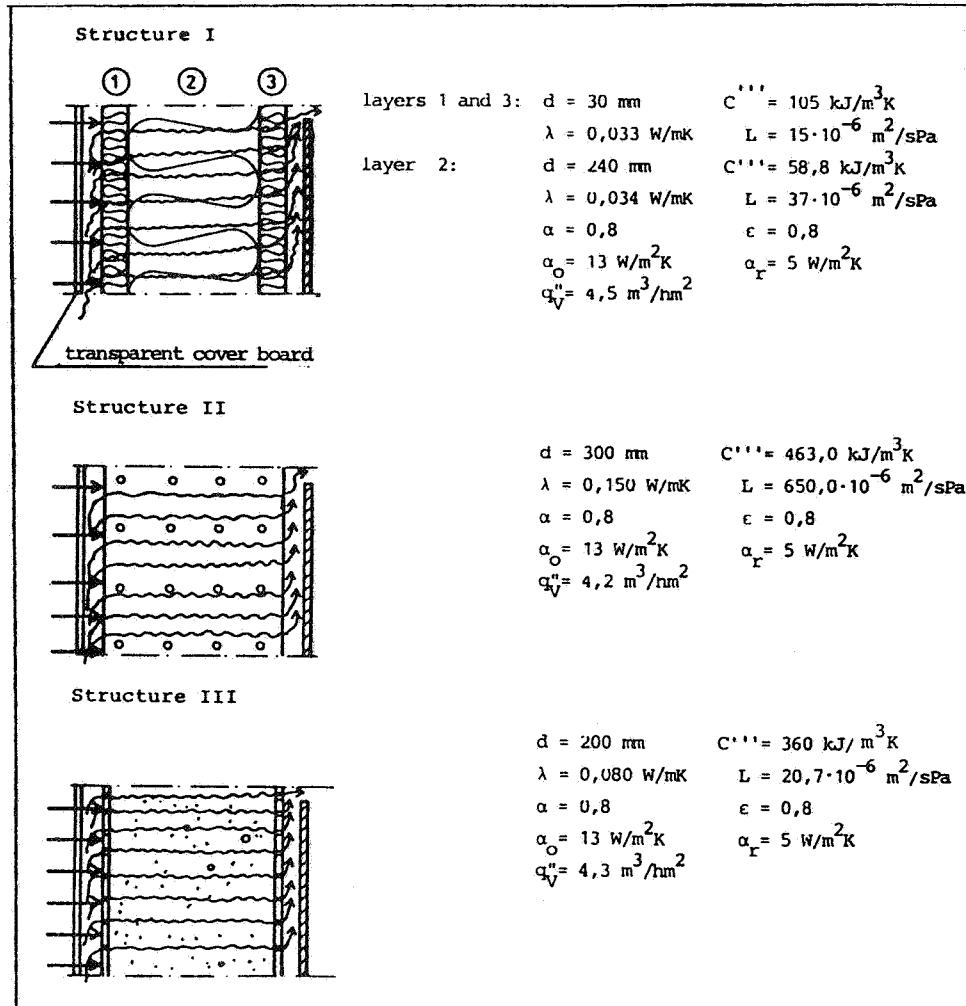


Figure 16. Wall structures in simulation and material properties.

In Fig. 18, the temperatures and the heat flux of the solar radiation are shown for a calculation period of three months.

Calculations show that the warming up of the incoming air is efficient in a porous body. The solar energy can be exploited most efficiently with a massive structure because it damps the surface temperature fluctuations effectively. The temperature of incoming air is occasionally rather high if thermally more light-weight structures are used (Fig. 18).

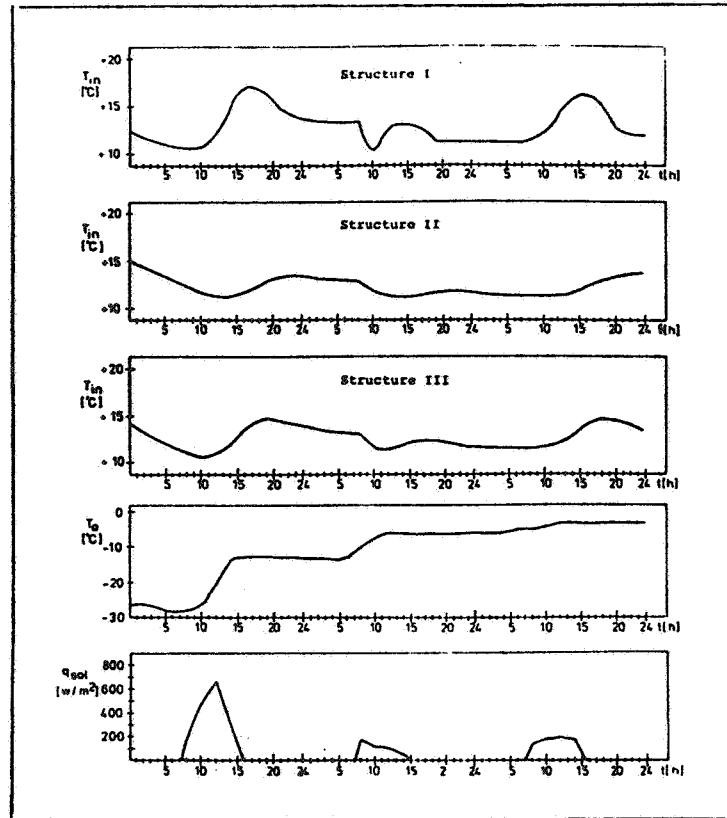


Figure 17. Temperatures of incoming air, the outside temperature and solar radiation for a three day period.

The pressure differences over the structures I, II and III were 13.0, 0.5 and 11.5 Pa, respectively. The inflow and outflow resistance factors were omitted. With high inflow and outflow resistance factors it is possible to make air flow diffusively, which is assumed in our calculations.

The degree hours of the longer calculation period (3 months) are $63 \cdot 10^3$ Kh, if the room air temperature is $+20^\circ\text{C}$. The total solar energy is 206 kWh/m^2 . From the conduction heat losses and solar radiation exploited energy, and the energy needed to warm up the incoming air up to the room air temperature are

	Structure I	Structure II	Structure III
Exploited energy (kWh/m ²)	53,5	51,1	50,7
Additional heating energy (kWh/m ²)	16,3	15,0	15,4
Volumetric flow rate (m ³ /hm ²)	4,5	4,2	4,3

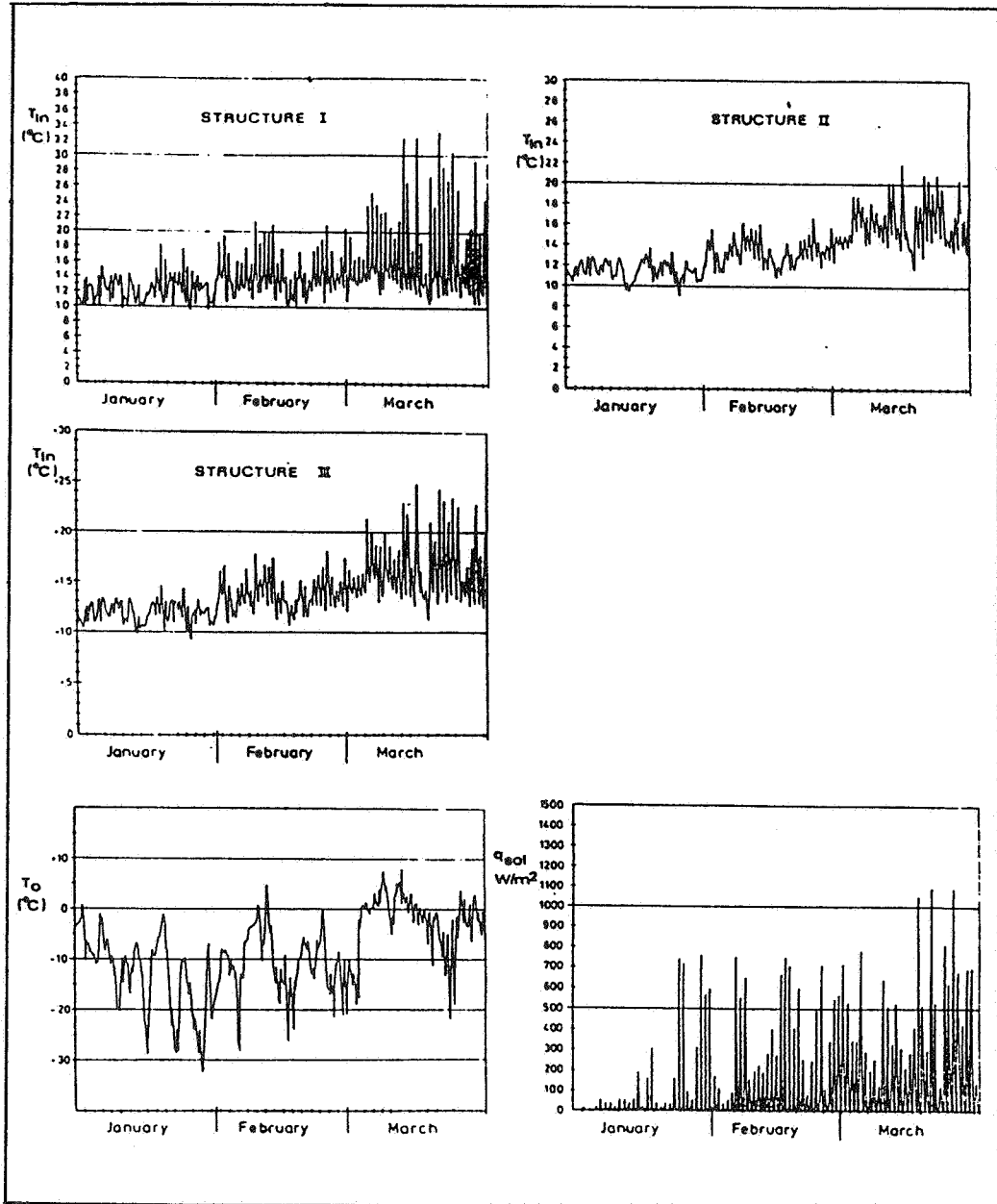


Figure 18. Temperatures of incoming air, the outside temperature and the solar radiation for a three month period.

According to our calculations the counter flow wall is a potential way to reduce the heating load of ventilation. In our further studies the thermal performance of integrated structures, including the counter flow wall, will be analyzed more thoroughly with more sophisticated calculation methods and experiments.

4. DISCUSSION AND CONCLUSIONS

The thermal coupling of leakage flows and heating load of buildings were studied by computer simulations and experiments. Based on the studies we suggest the transmission heat losses to be corrected by a Nusselt number typical for each structure and leakage flow pattern. The first approximation of the Nusselt number could be 0.8.

A clear difference should be made, whether the heat balance is formed for a room space or only for wall structure. In general, when considering a room or a building, ie., the coupling of building structures and, heating and ventilating systems, it is necessary to form the heat balance for a room space. It would also be reasonable to form the heat balance for a room space, for example, in the case the walls of a room have thermal coupling due to 3-dimensional internal air flows, which was omitted in our considerations.

Leakage flows have also influence on the dynamic behavior of wall structures. Heat flow field is two-dimensional, at least, and therefore at least two-dimensional approach should be applied. The finite difference method was found to be powerful in order to take into account the thermal coupling of leakage flows and transmission heat transfer. The time series approach, ie., the response factor approach seemed not to be useful because of strong nonlinearities.

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VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 11

VENTILATION RATES AND ENERGY LOSSES
DUE TO WINDOW OPENING BEHAVIOUR

P. WOUTERS¹, W.F. DE GIDS², P.R. WARREN³, AND P.J. JACKMAN⁴

¹ Belgian Building Research
Institute
Lombard Street 41
1000 Brussels
Belgium

³ Building Research Establishment
Building Research Station
Garston
Watford
United Kingdom

² TNO Division of Technology
for Society
PO Box 217
2600 AE Delft
Netherlands

⁴ Air Infiltration and
Ventilation Centre
Old Bracknell Lane West
Bracknell, Berkshire, RG12 4AH,
United Kingdom

SYNOPSIS

This paper describes one of the results of the IEA-annex 8 "Inhabitants behaviour with regard to ventilation".

Annex 8 has showed that the occupants can play a rather important role with regard to the ventilation rates in occupied buildings.

This paper gives some practical 'rule of thumbs' for estimating air flow rates through open windows.

An overview of measured and estimated ventilation rates in houses is given from which a simplified approach is derived that takes into account the air tightness of the building and the behaviour.

The second part of the paper deals with heat losses and seasonal heating demand due to window use. The effect of house type and insulation level is analysed as well as the variation in window use. This parameter study indicates that the effect of the window use on the energy consumption can be very important in apartments and well insulated houses.

1. INTRODUCTION

The International Energy Agency is coordinating several research-projects on ventilation. One of these researches is annex VIII "Inhabitants' behaviour with regard to ventilation". It was a two-year task sharing project which started in 1984.

The participants were : Belgium, Germany, Switzerland, The Netherlands and the United Kingdom. Mrs. C. Dubrul from the University of Namur, Belgium was the operating agent. The final reports ^{1,2} of this annex will be available in the second half of 1987.

One of the main objectives of this annex was the estimation of airflow rates and the amount of energy losses due to the ventilation behaviour of the inhabitants. One can find in § 2 of this paper estimations for air flow through open windows. Experimental and practical data for the increase in ventilation rates due to window use are given in § 3 and § 4. Finally, § 5 gives some results about heat and energy losses due to window use.

2. AIR FLOW RATES THROUGH OPEN WINDOWS

The air flow rate through an open window depends upon many factors, including those related to the building and its surroundings as well as prevailing wind and temperature conditions.

Windows also consist of different types, the geometry of which may, for a given area of opening, also affect the air flow. For present purposes it is proposed to develop relatively simple 'rules of thumb', based upon plausible assumptions, which can be used to estimate to a first order the ventilation rates resulting from window use.

These will be compared with the limited tracer gas measurements of the effect of window-opening on ventilation rate that are available.

It is useful at this stage to distinguish between the two main types of natural ventilation :

Cross-ventilation - in which spaces within the building are well-connected and air flow can readily occur through the building.

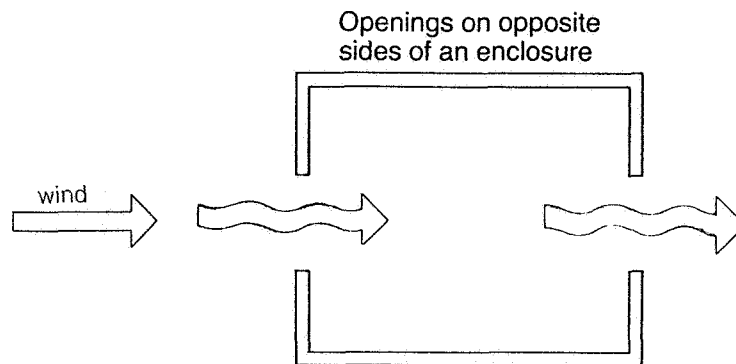


Figure 1 - Cross ventilation

Single-sided ventilation - in which the air flow from a room to the remaining parts of a building is severely restricted in comparison with the flow between the room and outside air.

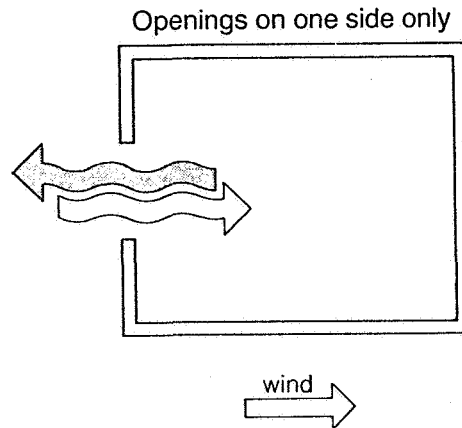


Figure 2 - Single-sided ventilation.

In the case of cross ventilation the ventilation rate of any one room depends upon the characteristics of the building as whole, whereas in singlesided ventilation the ventilation rate is independent of the remainder of the building.

2.1. Single-sided ventilation

The following expression for the volume flow rate of air through an open window due to single-sided ventilation can be used :

$$q_v = \frac{A_{\text{OPEN}}}{100} (B \cdot v^2 + 1.400 \Delta T \cdot h)^{1/2} \quad \text{in m}^3/\text{s}$$

where B lies between 1000 and 10.000, depending upon whether the window is sheltered or exposed to the wind.

Phaff et al³ have derived a similar empirical expression from measurements in Dutch dwellings in sheltered urban situations.

$$q_v = \frac{A_{\text{OPEN}}}{1000} (2500 + 250 V_{\text{REF}}^2 + 900 \Delta T \cdot h)^{1/2} \quad \text{in m}^3/\text{s}$$

Substitution of values for wind speed, V_{REF} and temperature difference, ΔT , typical of averaged values for the heating season in the Netherlands, Belgium and the United Kingdom, into the above equations shields the following 'rule of thumb' for the increase in ventilation rate for single-sided conditions :

$$q_v = (0,1 \text{ to } 0,25) A_{\text{OPEN}} \cdot V_{\text{REF}} \quad \text{in m}^3/\text{s}$$

This rule of thumb has been further confirmed by measurements of single-sided ventilation rate with a range of different window types by other workers ^{4,5}.

2.2. Cross ventilation

Similarly the following 'rule of thumb' has been derived for cross ventilation :

$$q_v = (0,4 \text{ to } 0,8) A_{\text{OPEN}} \cdot V_{\text{REF}} \quad \text{in m}^3/\text{s}$$

where A_{OPEN} is the summation of the areas of all open windows.

2.3. Definition of open area

The open area of a sliding window is well defined, but many windows consist of an opening light which projects out of the plane of the wall. In such cases the 'equivalent area' may be obtained by a series of measurements under controlled conditions with different degrees of window-opening as indicated in figure 3.

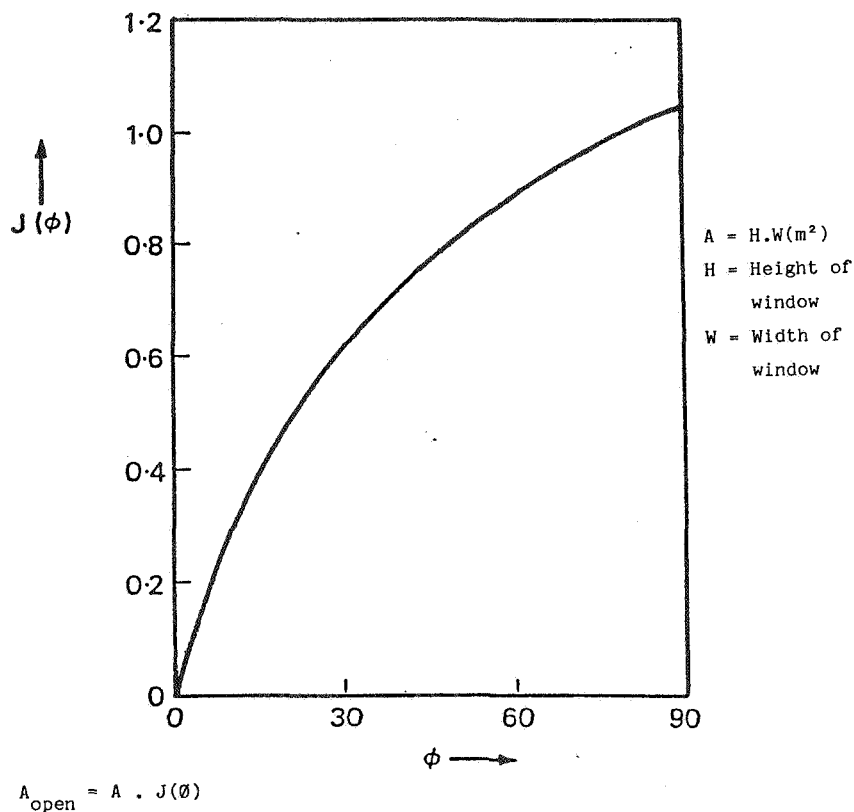


Figure 3 - Variation of open area with angle of opening ϕ .

3. AVERAGE WINTER VENTILATION RATES DUE TO WINDOW-OPENING

3.1. Direct measurements of the effects of occupant behaviour

Because of the difficulty of making continuous measurements of ventilation rate in occupied dwellings results are sparse. However, Kvisgard et al ⁶ have carried out a programme of measurements, using the constant concentration technique, in 25 Danish dwellings, 22 of which were occupied. Typically, measurements were made continuously over a period of one week. 14 of the dwellings were naturally ventilated, 6 had full input/extract mechanical ventilation and 2 had mechanical extract units only. A summary of the results for each of the naturally ventilated dwellings is given in table 1 and for the mechanically ventilated dwellings in table 2.

Nr	Volume (m ³)	η_{BAS} (h ⁻¹)	η_{TOT} (h ⁻¹)	$\frac{\eta_{\text{BAS}}}{\eta_{\text{TOT}}}$	Δn (h ⁻¹)	ΔnV (m ³ /h)	t_e (°C)	v (m/s)
1	162	0,01	0,94	94	0,93	151	0	4
2	184	0,12	0,52	4,3	0,40	74	6	4
3	261	0,14	0,22	1,6	0,08	21	3	1
4	351	0,15	0,20	1,3	0,05	18	6	5
5	271	0,15	0,27	1,8	0,12	32	-9	3
6	162	0,18	0,56	3,1	0,38	62	3	5
7	184	0,20	0,46	2,3	0,26	48	2	5
8	130	0,22	0,43	2,0	0,21	27	1	6
9	261	0,22	0,67	3,0	0,45	117	-5	4
10	299	0,22	0,38	1,7	0,16	48	-1	5
11	130	0,25	0,59	2,4	0,34	44	0	6
12	261	0,27	0,43	1,6	0,16	42	-8	4
13	205	0,27	0,38	1,4	0,11	23	-4	3
14	139	0,32	1,08	3,4	0,76	106	0	5
Mean	214	0,19	0,51	2,3	0,32	58	0	4,3
Stand. deviat.	70	0,08	0,25	0,9	0,26	40	5	1,3

Table 1 - Results for 14 Danish naturally ventilated buildings.

Nr	Volume (m ³)	η_{BAS} (h ⁻¹)	η_{MECH} (h ⁻¹)	η_{TOT} (h ⁻¹)	$\frac{\eta_{\text{TOT}}}{\eta_{\text{MECH}}}$	$\eta_{\text{TOT}} - \eta_{\text{MECH}}$ (h ⁻¹)	$\phi_{\text{TOT}} - \phi_{\text{MECH}}$ (m ³ /h)	t _e (°C)	v (m/s)
1	247	0,03	0,8	1,56	2,0	0,76	188	7	6
2	151	0,12	0,4	0,95	2,4	0,55	83	2	5
3	271	0,12	1,0	1,1	1,1	0,1	27	3	7
4	215	0,13	0,7	0,87	1,2	0,17	37	8	4
5	143	0,16	0,5	0,81	1,6	0,3	43	-2	6
6	355	0,22	0,45	0,55	1,2	0,1	36	5	6
7	205	0,28	0,5	0,80	1,6	0,3	61	0	5
8	247	0,30	0,7	1,14	1,6	0,44	109	8	4
Mean	229	0,17	0,63	0,97	1,6	0,34	73	4	5,4
Stand. Deviat.	68	0,09	0,20	0,30	0,4	0,23	54	4	1,1

Table 2 - Results for 8 Danish mechanically ventilated buildings.

A distinction is made between the total air change rate, η_{TOT} , which includes the effects of occupant behaviour and, η_{BAS} , the basic air change rate which occurs when the dwelling is unoccupied and all provisions for ventilation (windows, mechanical systems, etc ...) are shut off, and, η_{mech} , the air change rate provided by the mechanical system. Table 3 summaries the results from both groups of dwellings. It should be noted that for 36 % of the time the total ventilation rate in the naturally ventilated houses was below 0,25 h⁻¹, indicating that these Danish houses were probably substantially more air-tight than those found in most countries participating.

The increase in ventilation rate due to occupancy, η_{occ} , is, on average 0,32 in the naturally ventilated dwellings and 0,34 h⁻¹ in the mechanically ventilated dwellings. However, as might be expected, there is a large variation between individual dwellings, ranging from 0,1 h⁻¹ to 0,9 h⁻¹. The average increase in air flow rate, resulting from occupancy, varies from 20 tot 190 m³/h, with an average of 58 m³/h for naturally ventilated dwellings and 73 m³/h for the mechanically ventilated dwellings. There does not appear to be any association between the increase in air flow rate due to occupancy and either the basic air flow rate or the dwelling volume.

		Average		Variance	
		Natural ventil.	Mechanical ventilated	Natural ventil.	Mechanical ventilated
Dwelling volume	V (m ³)	214	229	70	68
Basic air change rate	η_{BAS} (h ⁻¹)	0,19	0,17	0,08	0,09
Ventilation rate with ventilation systems functioning	η_{MECH} (h ⁻¹)	-	0,63	-	0,20
Total air change rate	η_{TOT} (h ⁻¹)	0,51	0,97	0,25	0,30
Increase in air change rate due to occupancy	η_{OCC} (h ⁻¹)	0,32	0,34	0,26	0,23
Increase in air flow rate due to occupancy	$\eta_{\text{OCC}} \cdot V$ (m ³ /h)	58	73	40	54
External temperature	θ_e (°C)	0	4	5	4
Wind speed	v (m/s)	4,3	5,4	1,3	1,1
Number of occupants	OCC	2,9	2,6	1,0	0,9
• $\eta_{\text{TOT}} > 0,25 \text{ h}^{-1}$ (%)		64	99	29	1
• $\eta_{\text{TOT}} > 0,50 \text{ h}^{-1}$ (%)		24	77	18	20
• $\eta_{\text{TOT}} > 1 \text{ h}^{-1}$ (%)		9	34	9	22

Table 3 - Overview of the results for the 22 Danish houses.

3.2. Estimated effects of occupant behaviour

If the average pattern of window use is known for a particular house, then the approximate air exchange rates determined in § 2 may be used to estimate the resulting increment to average winter ventilation rate. This approach has been applied to results of an extensive questionnaire survey carried out by Wouters and De Baets in Belgian social housing⁸. The survey covered 100 housing estates and responses were obtained for 1115 single-family dwellings and 1219 apartments.

The results are described more fully elsewhere but two relevant conclusions may be summarised as follows :

- Some 30 % of all rooms are never aired. (The percentage is lowest for bedrooms but much higher for living-rooms).

- The average total daily periods of opening appear to be about 3 h, with higher values for bedrooms and lower values for living-rooms. Over all rooms (including those in which windows are never used) the average opening time is 2 h/day.

Using assumptions based upon the magnitude of flow rates discussed in § 2 the average increase in ventilation rate due to winter window-opening has been calculated for each dwelling in the survey. The overall results for single family dwellings and apartments are summarised in table 4. As indicated by the difference between the mean and median values for each group the distributions are highly skewed. The higher mean value for single family dwellings results from the fact that the window position was more often found to be wide open, as opposed to ajar, in this type of dwelling in comparison with the apartments.

Dwellings + Apartments		Individual dwellings		Apartments	
Mean	Median	Mean	Median	Mean	Median
0,26	0,10	0,31	0,14	0,21	0,09

Table 4 - Increase in ventilation rates due to occupancy (η_{OCC}) (h^{-1})^s
 Mean : arithmetical average Median : for 50 % of the buildings.

In addition to the Belgian study, a more limited investigation on one apartment building has been undertaken in Switzerland. This yielded an estimated increase in ventilation rate due to occupancy of $0,25 h^{-1}$.

3.3. Overview of results

Despite the assumptions and approximations made in deriving the estimated additional winter ventilation rates in the three studies discussed above, the results are remarkably similar (table 5).

source	country	description	(η_{OCC}) (ach)
Kvisgard et al	Denmark	. naturally ventilated	0,32
		. mechanically ventilated	0,34
Wouters and De Baets	Belgium	Single-family dwellings	0,31
		Apartments	0,21
Faist et al	Switzerland	Apartment	0,25

Table 5 - Overview of results for η_{OCC}

4. ESTIMATION OF VENTILATION RATES IN OCCUPIED DWELLINGS IN PRACTICE

Using the above results it is possible to derive a simple nomograph, shown in figure 4, for determining typical heating season ventilation rates in dwellings. This is based upon the following :

- (A) The seasonal 'basic' air change rate of a dwelling, in the absence of window-opening, may be derived from the air leakage at 50 Pa obtained from a pressurisation test, using the simple 'rule of thumb'

$$q_v = \frac{q_{vTOT}}{K}$$

where K lies between 10 and 30, the mean value of 20, may be regarded as typical. A guide to the appropriate choice of K is given below :

$10 \leq K \leq 20$: if a combination of at least 2 of the following characteristics is found :

- . High rise building
- . Exposed situation
- . Average winter meteorological wind speed greater than 4 m/s
- . Uniformly distributed leakage area.

$20 \leq K \leq 30$: if a combination of at least 2 of the following characteristics is found :

- . Individual terraced houses
- . Sheltered situation
- . Average winter meteorological wind speed less than 4 m/s
- . Leakage area mainly situated at high level.

(B) The results of the Belgian survey in Namur ¹ have indicated that there is no significant association between window use and the leakage characteristics, represented by q_{v50} . Thus,

$$n_{occ} \neq f(q_{v50})$$

(C) Similarly the survey by Kvisgard et al ⁶ indicates no significant association between window use and dwelling volume. Thus,

$$n_{occ} \neq f(\text{VOLUME})$$

(D) Further analysis of the studies by Wouters, De Baets ⁸ and Kvisgard et al ⁶ discussed previously in § 3 provides support for the following possible simple categorisation of additional average seasonal ventilation rate due to window use :

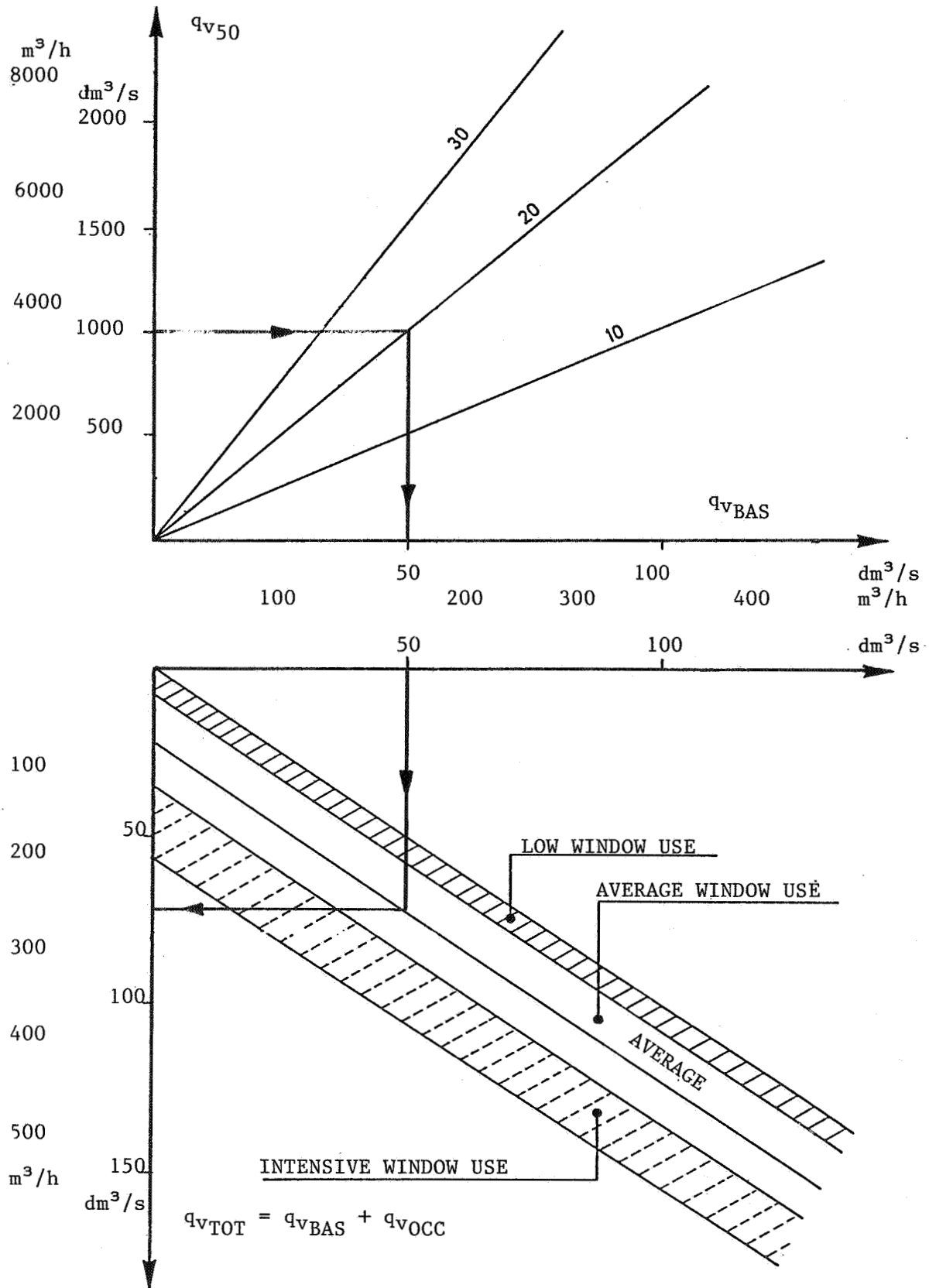
Low window use	: 0,0 to 0,1 h ⁻¹
Average window use	: 0,1 to 0,5 h ⁻¹
High window use	: 0,5 to 0,8 h ⁻¹ .

For an average dwelling of volume 250 m³, this leads to the following air flow rates :

Low window use	: 0 to 7 dm ³ /s (0 to 25 m ³ /h)
Average window use	: 7 to 35 dm ³ /s (25 to 125 m ³ /h)
High window use	: 35 to 55 dm ³ /s (125 to 200 m ³ /h).

The upper limit of high window use is not the absolute maximum value, it rarely will be exceeded in practice.

Figure 4



5. CALCULATION OF HEAT AND ENERGY-LOSSES

5.1. Heat losses due to ventilation and infiltration

This heat loss can be estimated by :

$$\phi_v = (q_{v_{INF}} + q_{v_{VENT}}) \rho \cdot c (T_i - T_e) \quad (W)$$

in which :

ϕ_v = heat losses due to ventilation and infiltration W
 c = specific heat of air J/kgK
 q_v = air flow rates m³/s

For $c = 1000 \text{ J/kgK}$ and $\rho = 1,23 \text{ kg/m}^3$ the above equation can be simplified :

$$\phi_v = 1230 (q_{v_{INF}} + q_{v_{VENT}}) (T_i - T_e) \quad (W)$$

If the air flow rate, q_v , is expressed in m³/h this equation becomes :

$$\phi_v = 0,34 (q_{v_{INF}} + q_{v_{VENT}}) (T_i - T_e) \quad (W)$$

Table 6 shows the heat losses for an air flow rate of 1 dm³/s and 1 m³/h for several temperature differences.

Ti - Te °C or K	Watt for 1 dm ³ /s	Watt for 1 M ³ /h
5	6,2	1,7
10	12,3	3,4
15	18,5	5,1
20	24,6	6,8
25	30,8	8,5

Table 6 - Heat losses for 1 dm³/s or 1 m³/h air flow rate.

5.2. Seasonal heating demand for infiltration and ventilation

The seasonal heating demand for ventilation and infiltration can be expressed as :

$$Q_v = \sum_s 4,4 (q_{v\text{VENT}} + q_{v\text{INF}}) (T_i - T_e) \quad (\text{MJ})$$

in which q_v is expressed in m^3/s . If q_v is expressed in m^3/h , than :

$$Q_v = \sum_s 0,34 (q_{v\text{VENT}} + q_{v\text{INF}}) (T_i - T_e) \quad (\text{Wh})$$

in which :

\sum_s = hourly summation over the heating season

q_v = air flow rate (m^3/s or m^3/h)

Taking into account the large uncertainty in practice, it is acceptable to use the degree-days approach.

$$Q_v = 1230 (q_{v\text{VENT}} + q_{v\text{INF}}) 86400 \cdot \text{DD} \quad (\text{J/ANNUM})$$

$$Q_v = 106 (q_{v\text{VENT}} + q_{v\text{INF}}) \text{DD} \quad (\text{MJ/ANNUM})$$

in which :

DD = Number of degree-days, over the heating season

q_v is expressed in m^3/s .

If q_v is expressed in m^3/h , than :

$$Q_v = 0,34 (q_{v\text{VENT}} + q_{v\text{INF}}) 0,024 \text{DD} \quad (\text{kWh/ANNUM})$$

Table 7 gives an overview of classical values of degree-days in the participating countries.

Country	Range of degree-days DD
Belgium	2100 - 3100
Netherlands	2600 - 3800
Switzerland	2500 - 5900
United Kingdom	1800 - 2600
West Germany	3200 - 4600

Table 7 - Variation in degree-days for a number of countries.

For most of the applications the number of degree-days varies from 1800-2600 in mild climates and 2100-3500 in more severe climates. Combination of these figures with equation (17) gives the following range in increase in heating demand per dm³/s increase of air flow rate :

mild $Q_v = 190 \text{ to } 280 \text{ MJ/ANNUM per dm}^3/\text{s}$
 severe $Q_v = 220 \text{ to } 370 \text{ MJ/ANNUM per dm}^3/\text{s}.$

or per m³/h increase of air flow rate :

mild $Q_v = 53 - 76 \text{ MJ/ANNUM per m}^3/\text{h}$
 severe $Q_v = 62 - 103 \text{ MJ/ANNUM per m}^3/\text{h}.$

Finally, a very rough estimation of the increase in energy consumption can be made. Table 8 gives an order of magnitude for the increase in electricity consumption, natural gas or fuel consumption. The (rough) assumption for the energy content of the alternative energy sources are given as well as the assumed efficiencies of the heating systems.

	energy content (rough estimate)	efficiency of heating system	increase in energy consumption for 1 dm ³ /s increase by ventilation
electricity	3,6 MJ/kWh	95 %	55 to 110 kWh
natural fuel oil	36 MJ/kWh	60 ... 70 %	8 to 16 m ³
consumption	36 MJ/kWh	60 ... 70 %	8 to 16 l

Table 8 - rough estimate of the relation 'air flow rate energy consumption' for an air flow rate of 1 dm³/s.

5.3. The heat losses for ventilation as a part of the total heat losses

It is common in many countries to assume a ventilation rate between 0,5 and 1 h⁻¹ for the calculation of the heat losses of rooms (NBN B62-003, DIN 4701, CIBS-guides).

Tables 9 and 10 give the main characteristics of the individual dwelling and apartment flat analysed in this chapter.

floor area	: 100 m ²
room height	: 2,5 m
volume	: 250 m ³
enveloppe	: 250 m ²
ventilation rate	: 1 h ⁻¹
average U-value of envelope	
case 1	: 2,0 W/m ² K (U _{glazing} = 5,6 W/m ² K, U _{wall} = 1,6 W/m ² K)
case 2	: 0,7 W/m ² K (U _{glazing} = 3,2 W/m ² K, U _{wall} = 0,56 W/m ² K)
case 3	: 0,4 W/m ² K (U _{glazing} = 1,6 W/m ² K, U _{wall} = 0,34 W/m ² K)

Table 9 - Assumptions for individual dwelling.

floor area	:	80 m ²
room height	:	2,5 m
volume	:	200 m ³
enveloppe	:	40 m ² (2 facades 2,5 x 8 m ²)
ventilation rate	:	1 h ⁻¹
average U-value of envelope		
case 1	:	4,0 W/m ² K (U _{glazing} = 5,6 W/m ² K, U _{wall} = 3,3 W/m ² K)
case 2	:	1,4 W/m ² K (U _{glazing} = 3,2 W/m ² K, U _{wall} = 0,63 W/m ² K)
case 3	:	0,8 W/m ² K (U _{glazing} = 1,6 W/m ² K, U _{wall} = 0,46 W/m ² K)

Table 10 - Assumptions for apartment flat.

Some comments on the average U-values :

- case 1 : typical value for an uninsulated building (single glazing, no insulation)
- case 2 : typical value for the present insulation level of new buildings (ordinary double glazing, 5 cm insulation in walls and roof)
- case 3 : typical value for a well insulated building (improved double glazing, 8 to 10 cm insulation in walls, 15 to 20 cm insulation in roof).

The higher corresponding U-values for the apartment flat are due to the high glazing percentage in the facades.

Table 11 gives the heat losses for transmission and ventilation for the 3 insulation levels and for a ventilation rate of 1 h⁻¹.

Average U-value (W/m ² K)		Transmission losses (W/K)		Ventilation losses (W/K)		Ventilation losses Total losses (%)	
House	Apartment	House	Apartment	House	Apartment	House	Apartment
2,0	4,0	500	160	85	68	15	30
0,7	1,4	175	56	85	68	33	55
0,4	0,8	100	32	85	68	46	68

Table 11 - Comparison of transmission and ventilation losses (n = 1 h⁻¹).

We can conclude :

1. the ventilation losses are relatively much more important in apartments.
2. the ventilation losses are becoming more and more important in better insulated buildings.
3. the high percentages in the well insulated buildings indicate that untight but well insulated buildings with high air change rates can have heating problems during cold periods with high wind speed if the heating system is designed according to the present standard. This problem can also occur in rooms of well insulated buildings with an overall moderate airtightness if some of the rooms are rather leaky and/or at the windward side.

5.4. The seasonal heating demand for ventilation as a part of the total heating demand

An estimation of the effect of ventilation losses on the seasonal heating demand gives usefull information. The heating demands given in this chapter were calculated according to the standardised calculation procedure for the French Region in Belgium.

Table 12 summarises the additional assumptions which were made for these calculations.

- . Average internal temperature :
 - case 1 : 17 °C (house) and 18 °C (apartment)
 - case 2 : 18 °C (house) and 19 °C (apartment)
 - case 3 : 19 °C (house) and 20 °C (apartment)
- . Glazing area :
 - house : 15 m² of which 6 m² to South and 3 m² to East, West and North
 - apartment : 6 m² to South and 6 m² to North (including shading)
- . Internal gains : 5 W/m²
- . Climatic data : Belgian Reference year

Table 12 - Assumptions for the calculation of the seasonal heating demand.

The results are given in tables below.

In the reference situation a ventilation rate of 0.5 h⁻¹ is assumed.

U (W/m ² K)	T _i (°C)	Ventilation rate (h ⁻¹)			
		0,5 (reference)	0,6 (low window use)	0,8 (average window use)	1,15 (high window use)
2,0	17	930	950	990	1050
0,7	18	320	340	380	440
0,4	19	200	220	260	330

Table 13 - Heating demand for the house (MJ/m², year)

U (W/m ² K)	T _i (°C)	Ventilation rate (h ⁻¹)			
		0,5 (reference)	0,6 (low window use)	0,8 (average window use)	1,15 (high window use)
4,0	18	360	380	420	490
1,4	19	120	140	175	240
0,8	20	75	95	135	210

Table 14 - Heating demand for the apartment (MJ/m², year).

In tables 15 and 16 is the heating demand due to window use expressed as a percentage of the total heating demand.

U _m (W/m ² K)	T _i (°C)	Low window use	Average window use	High window use
2,0	17	2	5	11
0,7	18	6	15	28
0,4	19	9	23	40

Table 15 - Percentage of total heating demand due to window use for house (%)

U_m (W/m ² K)	T_i (°C)	Low window use	Average window use	High window use
7,0	18	5	13	25
1,4	19	15	33	52
0,8	20	20	45	64

Table 16 - Percentage of total heating demand due to window use for apartment (%)

Interpretation :

- . For uninsulated dwellings (case 1) an average of 5 to 13 % of the heating demand is due to window use. For uninsulated houses this is almost never more than 10 %.
- . For moderate insulated dwellings (case 2) is on the average 15 to 33 % of the heating demand due to window use. It can reach 50 % for high window use in apartments.
- . In well insulated dwellings (case 3) is on the average 1/4 to 1/2 of the heating demand due to window use.
- . In uninsulated dwellings can differences in window use not explain big percentage differences in heating demand.

In well insulated dwellings and especially in apartments is the influence of the ventilation rate due to behaviour on the heating demand very great.

This means that a precise estimation of the heating demand in well insulated dwellings is much more difficult.

It is important to remember the reader that one should use the given data with care because the classification of the occupants in 3 classes (low, medium, high) is rather arbitrary and also because all the results are typical heating seasonal values.

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VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 12

VENTILATION REQUIREMENTS AND DEMAND
CONTROLLED VENTILATION

WILLIGERT RAATSCHEN AND LUTZ TREPTE

Dornier System GmbH
Post Box 1360
7990 Friedrichshafen
Federal Republic of Germany

LIST OF SYMBOLS

GW	material constant for particle board
T	temperature [K]
V	volume [m ³]
\dot{V}_{CO_2}	volume flow of CO ₂ -output [$\frac{1}{h}$]
a	particle board (pb) load [$\frac{\text{m}^2 \text{ pb}}{\text{m}^3 \text{ room}}$]
c	pollutant concentration [ppm]
\dot{m}_w	mass flow rate of water [g/h]
\dot{m}_w^*	specific mass flow rate \dot{m}_w/V_r [$\frac{\text{g}}{\text{hm}^3 \text{ room}}$]
n	hourly air charge rate [$\frac{1}{h}$]
θ	temperature [°C]
ϕ	rel. humidity [-]

Indices

i	indoor
o	outdoor
r	room

SYNOPSIS

In order to avoid damage to the health of occupants, annoyance or reduction in amenity and damage to the building fabric the concentration of indoor air pollutants has to be held below pollutant specific levels. One appropriate measure for the control of concentration is ventilation. In several national and international activities in the past, among others in the IEA's Annex IX "Minimum Ventilation Rates" and standardization efforts in Germany and other countries, ventilation rates have been defined which should meet both indoor air quality (iaq) requirements and energy conservation. The necessary air flow rates are, depending on the type of pollutant and national conditions, usually based on an average occupancy of persons in the room; they vary in a range of 30-40 m³/h and person. For comfort reasons the minimum ventilation rate necessary to maintain acceptable indoor air quality (iaq) depends on many influencing factors especially on the number of persons, seasons, time of the day etc..

Ventilation rates exceeding the real and actual demand are not energy economic. A general view of iaq requirements is given.

Natural ventilation systems are compared to the requirements of the proposed ventilation strategy. A state of the art is given for the use of simple ventilation devices. For conditions in the Federal Republic of Germany the arguments and the advantages for a ventilation strategy consisting of a basic ventilation for non-occupied rooms with an additional rate depending on the number of persons and their activity are outlined. Dominant influence factors for both basic ventilation and additional ventilation are pointed out.

1. INTRODUCTION

Table 1 shows contaminants identified as being of main concern for indoor air, their source and the influences on either occupants or building fabric. All these single influence parameters are of growing interest and today deeply investigated and published in technical journals.

influence parameter on iaq	depending on							
	independent on number of persons ³⁾	number of		the building's			certain activ. like painting, carpeting, repairs, cleaning	weather
		pers.	and their activity	insulation	furniture	environment		
moisture ¹⁾	x	x	x	x				x
carbon dioxide ²⁾		x	x					
body odour ²⁾		x	x					
formaldehyde ²⁾	x				x		x	
organic compon. ²⁾	x				x	x	x	
tobacco smoke ²⁾			x					
radon ²⁾	x					x		

Tab. 1: Dependence of influence parameters on indoor air quality (iaq)

- 1) may cause damages to the building fabric and may cause health problems to sensitive persons
- 2) may cause health problems to occupants
- 3) usually not persons or their activities giving rise to emissions

The objective of this paper is to weight these parameters, to inquire the impact of each parameter on iaq, and to find the most dominant parameters for monitoring and controlling purposes.

2. VENTILATION REQUIREMENTS

For energy savings the air flow rate through a room should not overshoot the air flow rate necessary to maintain good indoor air quality, but it also should not be lower to guarantee well-being of occupants and prevent damages to the building

fabric. As nearly every room in a house is frequented by the occupants at specific times of the day, there are always times when a room is not occupied and where ventilation rates can be shut down due to smaller amounts of emission. We will call this minimum ventilation rate "basic ventilation".

2.1 Basic Ventilation

For non-occupied rooms there are still indoor generated contaminants whose concentration has to be kept under a specific level.

2.1.1 Moisture Production

Water is evaporated by e.g. open surfaces (aquarium), flowers, wet clothes etc. The ventilation rate depends on the strength of water vapor released, the allowed rel. humidity inside the room depending on the interior surface temperature of the walls influenced by the insulation (thermal bridges!), and on the weather conditions outdoor temperature and humidity. At low outdoor temperatures the incoming air can remove much more indoor generated moisture than at higher outdoor temperatures. The variation of the relative humidity as a function of outdoor temperature for 13 locations distributed in the Federal Republic of Germany is listed in the German standard DIN 4710³⁾. An estimate for interior surface temperatures of walls which meet the German standard of minimal insulation requirements DIN 4108²⁾ has been published by Erhorn et al⁴⁾. Temperatures for non-occupied rooms vary between 16° and 22°C and may reach 14°C in bedrooms during wintertime.

Based on these information it is straightforward to calculate the necessary air flow rates to avoid surface condensation for the above specified boundary conditions. Figure 1 shows the so calculated air flow rates per 1 g/h water vapor production in

a room versus outdoor temperature with indoor temperature as parameter. The range of outdoor air humidity as a function of outdoor temperature according to DIN 4710 results also in a range for the calculated air flow rates. Fig. 1 also indicates, that the specific air flow rate $\frac{\dot{V}_o}{\dot{m}_w}$ slightly decreases when outdoor temperature increases from -15 to 5°C . At higher outdoor temperatures the specific air flow rates increase rapidly. For reduced room temperatures the specific air flow rates increase due to lower indoor surface temperatures of the walls. Appendix 1 shows the generalized calculation procedure.

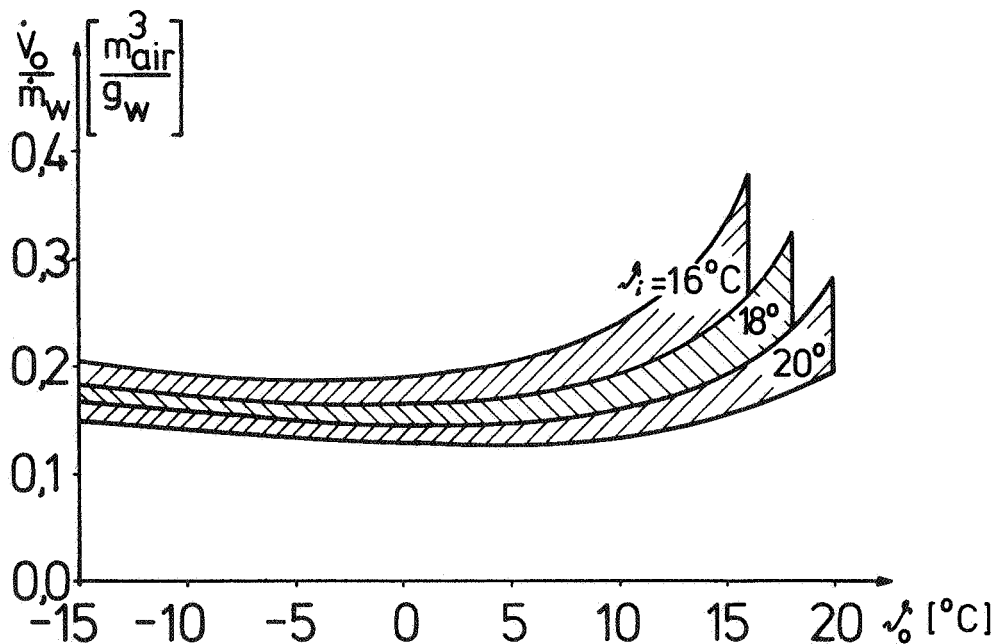


Fig. 1: Calculated outgoing air flow rates per 1 g/h water vapor production for avoiding condensation on interior wall surfaces

Therefore, a night switch back of a heating system to save energy will not decrease ventilation heat losses in the same magnitude than transmission heat losses if the then required higher ventilation rates at lower indoor temperatures are

realized. As shown in figure 2 a reduction of the ventilation heat demand is only achieved at outdoor temperatures above 0°C.

Although the air flow rate has to be increased at lower indoor temperatures the smaller temperature differences $t_i - t_o$ are responsible for this reduction. When outdoor temperatures are below 0°C, the higher air flow rates are dominant and the result is an even higher ventilation heat demand. This graph is only partly true. Night switch back is a dynamic process and interior-wall-surface temperatures will not follow the change in indoor air temperature without hysteresis due to the inertia of the system.

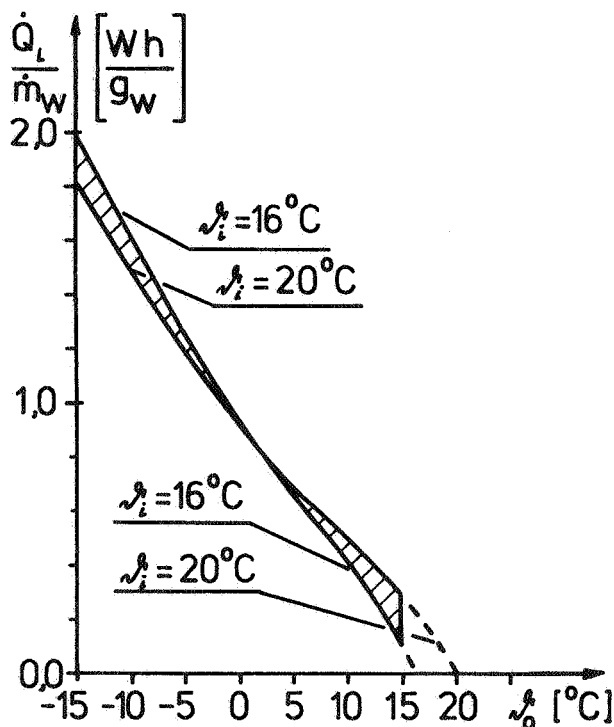


Fig. 2: Specific heat demand for ventilation (related to an evaporation rate of 1 g water per hour) for 2 indoor air temperatures with mean values of $\frac{\dot{V}_O}{\dot{m}_W}$ according to figure 1

2.1.2 Formaldehyde emission

Formaldehyde HCHO is mainly released by furniture made of particle board. In the Federal Republic of Germany only particle board of emission class E1 is allowed in prefabricated houses and for the production of furniture. Investigations of Mehlhorn^{1 2)} show that the emission of HCHO depends on a material constant, the room temperature and relative humidity, the air flow rate and the particle board load in the room. According to Fischer et al⁹⁾ an average value for the load factor of German houses is

$$a = 1 \frac{\text{m}^2 \text{ particle board}}{\text{m}^3 \text{ room}}$$

The load factor 'a' may rise to values of 2 for rooms with a high packing fraction of furniture. The emission of HCHO increases with increasing temperature, humidity, material constant, load factor and air flow rate. The calculation procedure of minimum ventilation rates to keep indoor HCHO concentration below a specific level is outlined in Appendix 2. For regulatory purposes it is recommended to limit the indoor air concentration to values below the experimental no effect level by applying a safety factor. This concentration is called "Acceptable Indoor Concentration, AIC", introduced by Fischer⁸⁾. The Federal Health Office of Germany recommended an AIC for formaldehyde of $\text{AIC}_{\text{HCHO}} = 0,1 \text{ ppm} (= 0,12 \text{ mg/m}^3)$.

2.1.3 Comparison of minimum air change rates for removal of moisture and formaldehyde

Water vapor production of non-occupied rooms and HCHO emission vary considerably according to the kind of room. To get an idea of the magnitude of the considered minimum air change rate (ACR) two cases are considered:

a) a non-occupied bathroom with a water evaporation rate of
 $\dot{m}_w^* = 3 \left[\frac{\text{g}}{\text{h} \cdot \text{m}^3_{\text{room}}} \right]$

representing - an open water surface of 0,4x0,4 m

- or 0,7 kg wet towels

- or 2-3 pot-plants

$V_{\text{room}} = 10 \text{ m}^3$; $\rho_i = 16-20^\circ\text{C}$; $\xi_o(\rho_o)$ according to DIN 4710
 (see Appendix I)

particle board load factor $a = 0,5 \frac{\text{m}^2}{\text{m}^3}$

ξ_i calculated by eqn. 5, Appendix I, $\text{AIC}_{\text{HCHO}} = 0,1 \text{ ppm}$

$$\dot{m}_w^* = \frac{\dot{m}_w}{V_r}$$

b) a living room with a water evaporation rate of

$$\dot{m}_w^* = 2 \left[\frac{\text{g}}{\text{h} \cdot \text{m}^3_{\text{room}}} \right]$$

representing for example - 12 pot-plants

- or an Aquarium of 1 m x 0,6 m

$V_{\text{room}} = 60 \text{ m}^3$; $\rho_i = 16-22^\circ\text{C}$; $\xi_o(\rho_o)$ according to
 DIN 4710, see Appendix I,

particle board load factor $a = 1,0 \frac{\text{m}^2}{\text{m}^3}$

ξ_i calculated by eqn. 5, Appendix I, $\text{AIC}_{\text{HCHO}} = 0,1 \text{ ppm}$

Figure 3a and 3b show minimum ACRs at 3 outdoor temperatures to either remove moisture or formaldehyde. The shaded areas indicate the range of ACRs due to changes in outdoor air humidity and indoor air temperature. The hourly ACRs in the bathroom according to figure 3a to keep HCHO concentrations below 0,1 ppm are equal or less than the hourly ACRs to remove moisture. This is due to the small load factor of $a = 0,5 \frac{\text{m}^2}{\text{m}^3}$. The significant decrease in HCHO emission at $\rho_o = -10^\circ\text{C}$ is due to the small allowed relative indoor humidity to avoid surface condensation. With a relatively high evaporation rate of water of $\dot{m}_w^* = 3 \frac{\text{g}}{\text{hm}^3_{\text{room}}}$ moisture is the dominant factor.

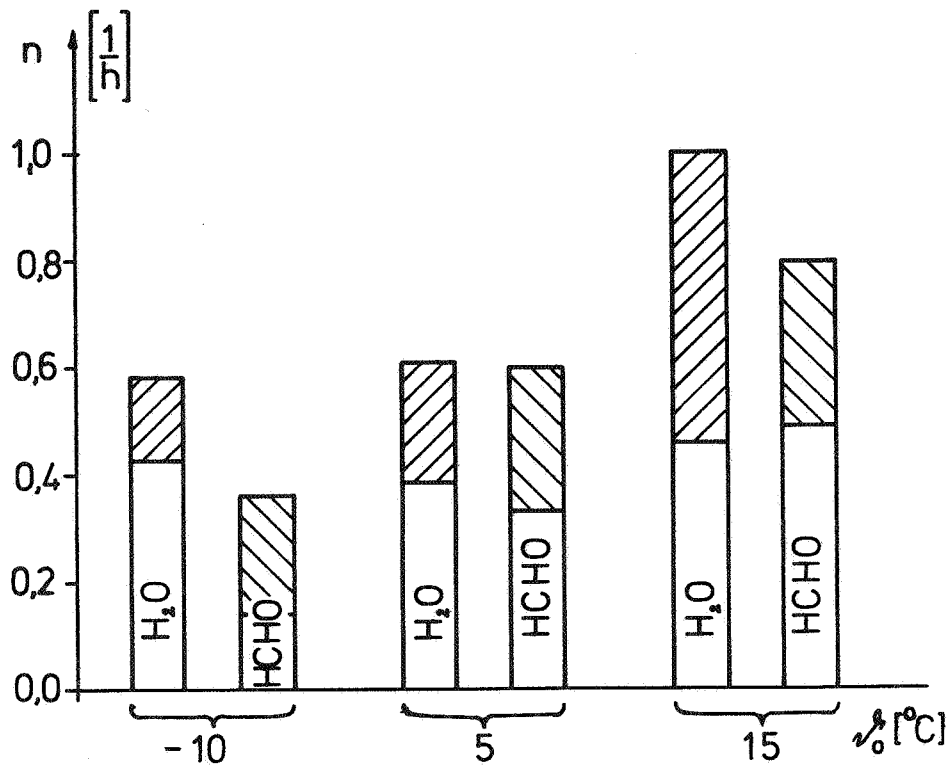


Fig. 3a: Hourly air change rate to remove moisture or formaldehyde in a bathroom

$$V_r = 10 \text{ [m}^3\text{]}; \dot{m}_w^* = 3 \text{ [} \frac{\text{g}}{\text{hm}^3}\text{]}; \vartheta_i = 16-20^\circ\text{C}$$

$$a = 0,5 \text{ [} \frac{\text{m}^2}{\text{m}^3}\text{]}; \text{AIC}_{\text{HCHO}} = 0,1 \text{ ppm}$$

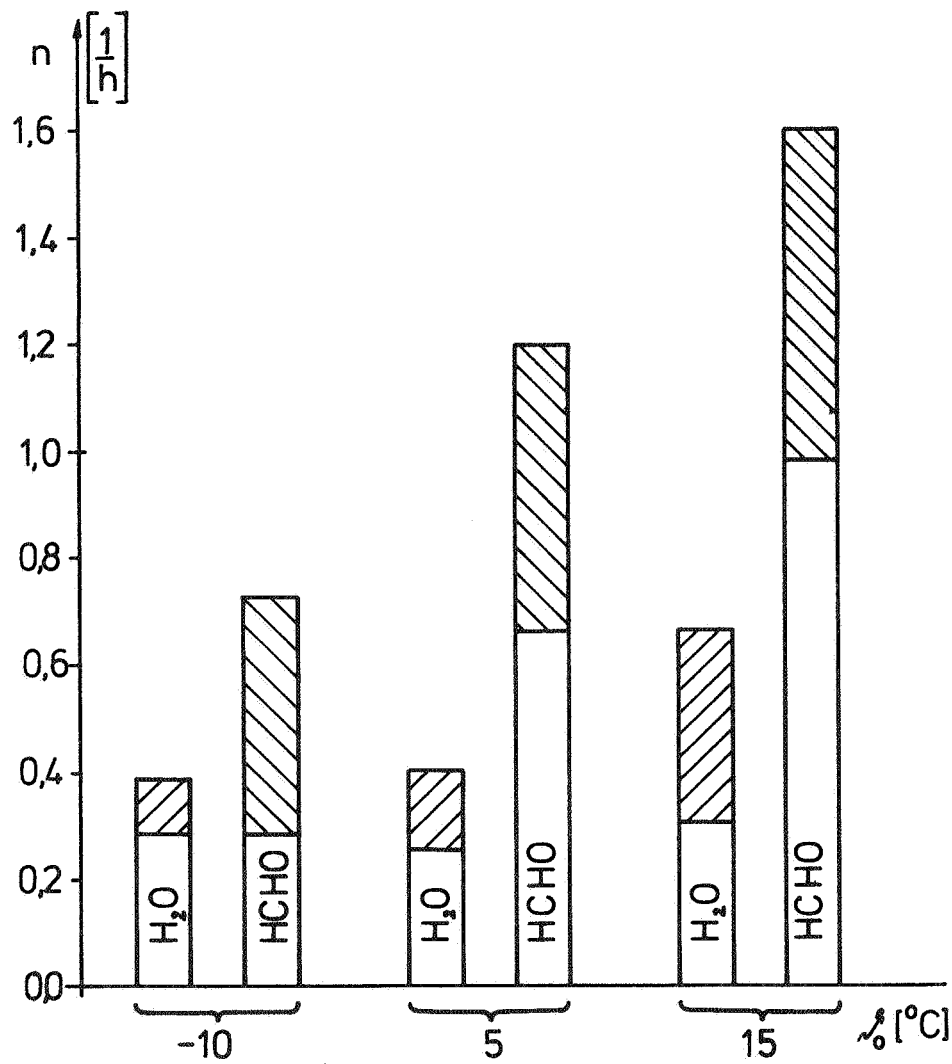


Fig. 3b: Hourly air change rate to remove moisture or formaldehyde in a living room

$$V_r = 60 \text{ [m}^3\text{]}; \dot{m}_w^* = 2 \text{ [}\frac{\text{g}}{\text{hm}^3}\text{]}; \theta_i = 16-20^\circ\text{C}$$

$$a = 1 \text{ [}\frac{\text{m}^2}{\text{m}^3}\text{]}; \text{AIC}_{\text{HCHO}} = 0,1 \text{ ppm}$$

The same calculation procedure applied to an average living room with a load factor $a = 1 \frac{\text{m}^2}{\text{m}^3}$ and a room volume of 60 m^3 shows a reverse behaviour. Due to a smaller evaporation rate of water and a higher load factor formaldehyde is the dominant parameter.

It should not be the objective of ventilation to remove indoor generated contaminants like HCHO or PCP, the primary step should be either to avoid emitting materials or to reduce their emission rates. However, based on emission standards which are valid at this time in the FRG it can happen that HCHO concentration reach irresponsible levels as it is indicated in figure 3b.

Another example may emphasize the importance of a basic ventilation rate. If there is no ventilation ($n=0.0\frac{1}{\text{h}}$) HCHO-concentrations in a room can easily reach levels of 0.25 ppm, this is when for a typical spring or fall day the relative indoor humidity is 90 %, room temperature 20°C , $\text{GW} = 3,5$ and the load factor $a = 1 \frac{\text{m}^2}{\text{m}^3}$.

Because of this fact in further investigations of average German houses techniques of following the dominant regime will be developed.

If ventilation rates are lower, the indoor humidity and HCHO-concentration increase. A considerable amount of e.g. HCHO can be adsorbed by carpets, drapes, furnitures etc. (Seifert¹³) but it should not be an objective of energy saving to include desorption processes in strategies and that the built up concentrations are put down when people enter the room. At this time it is also not known, how short peaks in relative humidity due to adsorption processes of moisture on walls influence the possibility of mould growth there. For this reason all considerations introduced here do not account for these effects. They also do not account for non-perfect ventilation

efficiency; it is always assumed that gases are completely mixed.

The amount of ACR necessary to avoid mould growth on one hand and to keep indoor air concentration of HCHO under a certain level behave contrarily. If indoor temperature is high the ACR to draw off the indoor generated moisture can be kept down where as the ACR to draw off the released HCHO must increase. Both calculated ACRs vary very much dependent on indoor temperature and humidity, amount of released moisture, load factor of particle board and acceptable indoor concentrations.

The quality of the wall insulation has a major impact on the calculated air flow rates necessary to remove moisture. Better insulated houses have higher interior surface-wall temperatures so that indoor air humidity can be higher and ACR lower.

2.1.4 Radon

A third influence factor on iaq which is independent of the occupancy of a room is radon. Radon-222 and Radon-220 is produced by the radioactive decay of Radium-226 and Thorium-232 nuclides.

The Radon-220 isotope has a halflife of only 54.5 seconds, whereas the Radon-222 has one of 3.8 days (Ericson et al⁵). It can partly move from the building material or the soil adjacent to the building and mix with indoor air. The inhaled radioactive noble gases are of minor importance for the radiation dose of people, as they are inert and don't stay in the respiratory tract. Of importance are their radioactive decay products like polonium, bismuth, and lead. Attached to airborne aerosoles they enter the respiratory system and contribute to the radiation exposure of the lung.

Ericson⁶⁾ reported mean indoor radon concentrations of 17 Bq/m³ for the building stock of the Federal Republic of Germany, newer investigations published by Keller¹¹⁾ show mean values of 20-70 Bq/m³. This shows a great increase up to a factor of 4 as it was also realized in Sweden. These two figures may not be compatible as they do not cover the same area and houses and there is no information about ventilation rates in the monitored houses.

However, high ventilation rates should not be applied to reduce indoor radon concentration. Radon emissions should be minimized through restrictions for building material. It doesn't seem to be appropriate to introduce the radon concentration as a control parameter for ventilation.

2.1.5 Other Components

It seems to be appropriate to look only at pollutants, to which occupants are exposed over a long term. E.g. odours from fresh paint or the exposure to a casually applied insecticide may lead to short term increased ventilation and will be excluded in further considerations. Incoming contaminants from outdoor air can only be handled through special devices (e.g. filters) and are excluded too.

In conclusion, the above stated considerations show, that a basic ventilation is required. The necessary level could be discussed e.g. by statistical means and standards of german housing stock. As control parameter for basic ventilation rate one must check, if moisture or HCHO-production is predominant.

2.2 Occupied houses

Most contaminants of indoor air are caused by humans and their activities.

2.2.1 Moisture production

In occupied rooms we have additional moisture emission by humans themselves, by cooking, washing, showering, intake of wet clothes, etc.

Based on figure 1 with a mean outside humidity figure 4 enables - with indoor temperature and moisture emission as parameter - the determination of hourly ACRs to remove moisture.

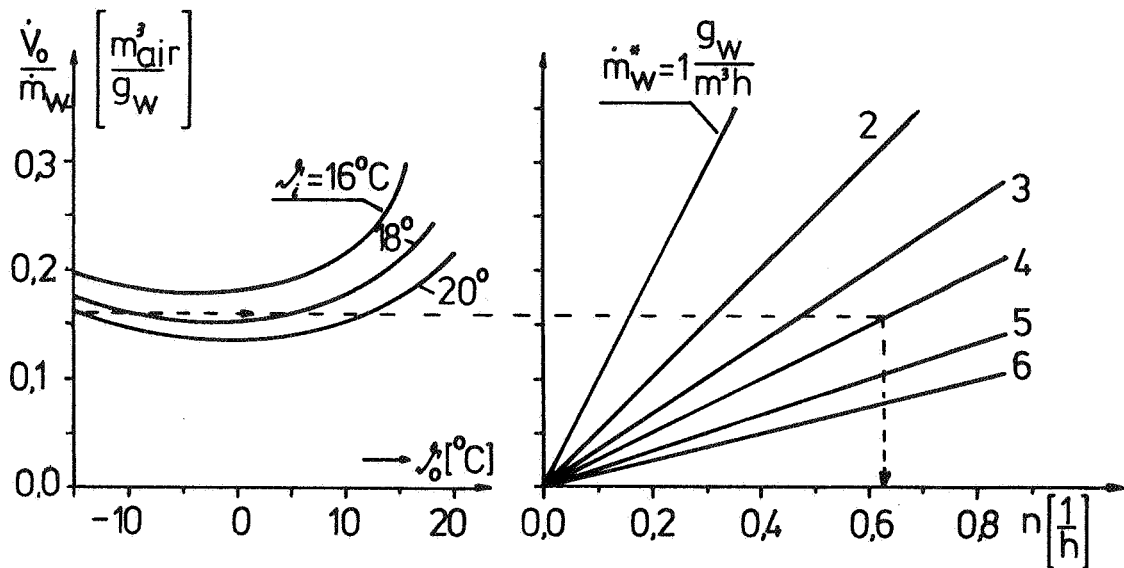


Fig. 4: Nomogram to obtain the hourly air change rate to remove moisture as a function of the source strength of water

For an average living room of 60 m³ and an occupancy of 3 persons with an evaporation of $4 \frac{\text{g}}{\text{hm}^3_{\text{room}}}$ water and outdoor temperatures below +10°C we see that an hourly ACR of $n = 0,63 \frac{1}{\text{h}}$ is necessary, when no condensation at surfaces and adsorption effects should occur and no other water vapor sources are present.

2.2.2 Carbon dioxide (CO₂) and body odour

According to Tamura¹⁴⁾ the CO₂ output for an average sedentary adult is $18 \frac{1}{\text{h}}$. The necessary ACR to keep the CO₂ concentration below a certain level is calculated by

$$n_{\text{CO}_2} = \frac{\dot{V}_{\text{CO}_2}}{V_R \cdot (c_i - c_o)} \cdot 10^3$$

Respiration problems of persons were first observed at 10.000 ppm CO₂ in the air. These high levels are usually not reached in a room.

However, studies of Berg-Munch et al¹⁾ indicate that carbon dioxide can be well correlated with the intensity of body odour. The therefore proposed limits of CO₂ in rooms for European countries range from 1000 to 1500 ppm. For the reason of keeping a room odour-free CO₂ seems to be a suitable control parameter.

To keep CO₂ concentrations below 1500 ppm the necessary ACR versus CO₂-output with room volume as parameter is shown in Fig. 5.

For commonly occupied dwellings these ACRs are lower or in the range of the basic ventilation rates. From the point of view of a health risk CO₂ is not an appropriate control parameter.

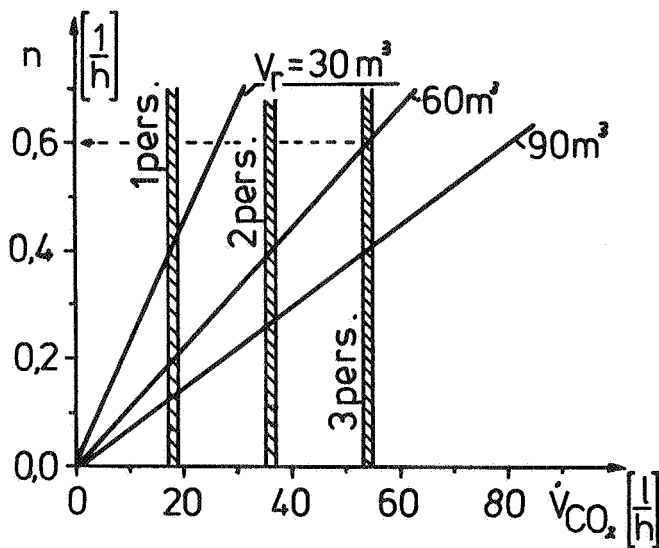


Fig. 5: Hourly air change rate necessary to keep indoor room concentration of CO_2 below 1500 ppm (outdoor concentration of $\text{CO}_2 = 0$)

As CO_2 and water-vapor output by humans is linked one can check which factor is dominant. Keeping the previous example of a living room with 3 occupants in mind, figure 4 gave a minimum hourly ACR of $0.63 \frac{1}{h}$ for the removal of moisture. These 3 persons have a CO_2 -output of $54 \frac{l}{h}$. According to figure 5 an hourly ACR of $0.6 \frac{1}{h}$ is necessary to keep the CO_2 level below 1500 ppm. For outdoor temperatures between $10\div 15^\circ\text{C}$ or lower indoor temperatures the ACR to remove moisture is higher and the CO_2 concentration is in the proposed range or even below 1000 ppm. This shows that if a room is adequately ventilated based on moisture control, there will usually be no problems with body odour.

These considerations may not be appropriate for schools, theatres or assembly halls, where CO_2 production may overshoot the production of moisture.

2.2.3 Tobacco smoke

Tobacco smoke is very annoying to many persons and it often decreases iaq to a non-acceptable limit. According to Wanner¹⁵⁾ tobacco smoke consists of a complex mixture of several thousand chemical compounds; carbon monoxide, nicotine, particulate matter, tar or condensate are the dominant one's. Wanner found that an air flow of 33 m³/h is necessary in order to keep carbon monoxide (CO) concentrations below a proposed maximum allowable level of 2 ppm. An indoor air concentration of only 1 ppm CO (air flow rate of 66 m³/h per person and cigarette) is needed to avoid eye irritation. Therefore, if smokers are present in a room, much higher ventilation rates are needed. CO may be an acceptable monitoring parameter for tobacco smoke. Also particulates or other substances have been discussed as control parameter for tobacco smoke. The recommendations are in the order of 70 m³/h per person, sometimes even total separation of smoking and non-smoking areas is recommended.

In conclusion:

- for non-occupied rooms moisture and HCHO can be of a critical magnitude and either one of them can be dominant for the amount of basic ACR needed
- for occupied rooms the moisture release is dominant. Body odour should not be a major problem, when ACR are high enough to remove moisture. If smokers are present ventilation rates have to be much higher.

3. STATE OF THE ART AND VENTILATION STRATEGIES

The requirements to a ventilation system are primarily set up by achieving and maintaining good iaq. The ventilation rates necessary depend on outdoor conditions (weather, air pollution) inside conditions (persons, their activity, furniture, sort of room, etc.). From IEAs Annex IX "Minimum Ventilation Rates" we know the outdoor air supply needed for comfort and appropriate iaq. A first step to energy conservation is to hold ventilation rates on levels needed for health and comfort reasons. In practice this means to realize demand controlled ventilation. A further step is heat recovery.

Ventilation is up to now in the Federal Republic of Germany mostly realized by

- natural ventilation, in newer houses also by
- simple ventilation devices, and only to some extent by
- exhaust, supply or balanced ventilation systems,

Here we will only discuss the first two techniques briefly.

3.1 Natural ventilation

Natural ventilation is strongly influenced by wind and temperature differences between indoor and outdoor. As the wind blows arbitrarily its impact is very unpleasant and difficult to avoid in natural ventilated houses.

According to figure 1, there is only a much smaller amount of air flow needed, when the difference between indoor and outdoor temperature is high (winter time); but especially during that time thermal effects on natural ventilation systems are highest, i.e. outdoor temperature effects a natural ventilation system contrarily. If one wants to ensure the removal of moisture with a natural ventilation system, air change rates

are either too low or too high. With common building design, where ventilation is achieved by infiltration through gap leakages, cracks in the building envelope or opening of windows, no acceptable iaq and a simultaneous energy efficient ventilation system can be realized.

Although natural ventilation remains the cheapest way to ventilate a building one has to check how higher ACRs effect the increase in energy costs and well-being of occupants.

3.2 Simple devices

If the lay-out of purpose provided openings in the building envelope is done in the way to meet basic ventilation needs during the wintertime for a mean wind speed and temp. difference, when the smallest ventilation rate is needed, one can think about simple devices, controlled by the user or temperature to increase ventilation during other times of the year (controllable slot vents in windows, levers to adjust the opening area of windows, stacks).

The advantage of these simple passive devices is an usually low price and the possibility for the user to interfere. As a human being is not sensitive to the relative humidity, it will happen that the ventilation rate must be greater than the occupant thinks.

The interference of the user is needed and well desired especially to increase ventilation in case of smoking. For the removal of moisture the system should act by itself.

A promising work is reported from Johnson et al¹⁰⁾, who tested passive ventilation systems with especially developed devices in some houses of the UK. Their systems consisted of controllable slot vents in all windows and exhaust tubes in the bath and kitchen.

Similar tests have been performed in Sweden by Eriksson et al⁷⁾, who used temperature controlled slot vents in windows. The recent results are very promising and encouraging for the future work in this field.

4. CONCLUSIONS

To maintain an acceptable iaq and to operate an energy efficient ventilation system it is advisable to supply a room with a basic air flow rate when it is not occupied and add an additional flow rate, when occupants are present. At the present situation of insulation and emission standards in the Federal Republic of Germany, evaporation of water and emission of HCHO in non-occupied rooms can be dominant depending on the sources, building insulation and season. The amount of the additional ventilation rate depends mainly on the source strength of water vapor in the room. A humidity sensor may be a good way to ensure good iaq. In rooms with smokers the necessary ventilation rates have to be much higher to avoid annoyance caused by smoke. A CO sensors is appropriate to control ventilation rates if smokes are present. Most houses in the Federal Republic of Germany are ventilated by natural ventilation which doesn't fulfill the requirements to iaq and energy savings. There has been much encouraging progress in achieving good results with simple ventilation devices. This should be the objectives in further r and d projects.

5.

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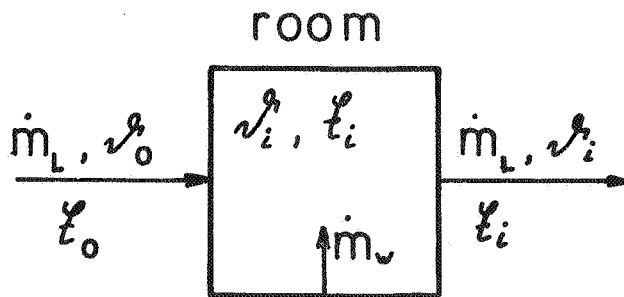
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Appendix I:

For steady state conditions, no absorption or desorption effects, and no condensation at window glasses, the continuity equation applied to a room with indoor water vapor sources and in- and outgoing air is



$$\dot{m}_L \cdot X_o + \dot{m}_w = \dot{m}_L \cdot X_i$$

\dot{m}_L = mass flow rate of dry air [$\frac{\text{kg}}{\text{s}}$]

X_o = water content of outdoor air [$\frac{\text{kg}_{\text{water}}}{\text{kg}_{\text{dry air}}}$]

X_i = water content of indoor air [$\frac{\text{kg}_{\text{water}}}{\text{kg}_{\text{dry air}}}$]

\dot{m}_w = indoor generated water vapor flow rate [$\frac{\text{kg}}{\text{s}}$]

ϕ_o = rel. humidity outdoor [-]

ϕ_i = rel. humidity indoor [-]

ρ_o = temperature outdoor [$^{\circ}\text{C}$]

ρ_i = temperature indoor [$^{\circ}\text{C}$]

T_o = temperature outdoor [K]

T_i = temperature indoor [K]

$$\dot{m}_L = \frac{\dot{m}_w}{X_i - X_o} \quad (1)$$

with eqn. 1 and ideal gas law applied to a mixture of dry air and water vapor, the outgoing volume flow rate \dot{V}_o is given by

$$\frac{\dot{V}_O}{\dot{m}_W} = \frac{1}{X_i - X_O} \cdot \frac{R_W \cdot T_i}{p} \left(\frac{M_W}{M_L} + X_i \right) \quad (2)$$

where $R_W = 461 \left[\frac{J}{kg \cdot K} \right]$ is the gas constant of water vapor

$p = 10^5 \text{ [Pa]}$ is the ambient pressure

and $\frac{M_W}{M_L} = 0,622$ mole ratio of water and air

The maximum rel. indoor air humidity is calculated so that no condensation occurs on the coldest interior surfaces of the walls. These are usually the exterior walls. The lowest surface temperature of a wall which meet the FRG insulation standard DIN 4108 are to be found in 2- or 3-dimensional corners. According to Erhorn et al⁴⁾, the surface temperature θ_i^S can be estimated by

$$\theta_i^S = \theta_O + 0,63 \cdot (\theta_i - \theta_O) \quad (3)$$

from this the water content X_i is calculated by

$$X_i = \frac{p_S(\theta_i^S)}{\varphi_i^S \cdot p - p_S(\theta_i^S)} \cdot \frac{M_W}{M_L} \quad (4)$$

p_S = saturation vapor pressure of water [Pa]

φ_i^S = rel. humidity at the surface of the wall ≤ 1.0

Transforming eqn. (4) we get the expression for the maximum rel. humidity inside the room to

$$\varphi_i = \frac{p}{\frac{p_S(\theta_i)}{X_i} \cdot \frac{M_W}{M_L} + p_S(\theta_i)} \quad (5)$$

The water content of the outdoor air is analogous to eqn. (4)

$$X_O = \frac{p_S(\vartheta_O)}{\frac{p}{\varphi_O} - p_S(\vartheta_O)} \cdot \frac{M_W}{M_L} \quad (6)$$

According to DIN 4710 the variation of outdoor humidity as a function of outdoor temperature gives table 2.

ϑ_O [°C]	-10°	0°	10°	20°
φ_O [-]	0,65-0,95	0,68-0,88	0,70-0,83	0,71-0,8

Tab. 2: Range of rel. outdoor humidity as a function of outdoor temperature for 13 locations spread over the FRG according to DIN 4710

With input parameters ϑ_O , φ_O , ϑ_i eqn. (2) can be calculated. A plot of $\frac{\dot{V}_O}{\dot{m}_W}$ versus ϑ_O with parameter ϑ_i shows figure 1.

Appendix II:

According to Mehlhorn^{1,2)} the equation to determine the HCHO concentration in a ventilated room is given by

$$c = \frac{4.37 \cdot 10^{-5} \cdot (GW - 0,046) \cdot \varphi_i^{-6,07} \cdot (\vartheta_i + 32,3)}{1 + \frac{n}{a} \cdot 0,968}$$

c = HCHO concentration [ppm]

GW = material constant (< 3,5 for particle board FRG emission class E1)

ϑ_i = rel. humidity in %

n = hourly ACR [$\frac{1}{h}$]

a = load factor [$\frac{m^2}{m^3}$]

validity range:

temperature $15^\circ < \vartheta_i < 30^\circ C$

rel. humidity $26 < \vartheta_i < 82 \%$

hourly air change rate $0,4 < n < 3,0 \frac{1}{h}$

load factor $0,2 < a < 1,16 \frac{m^2}{m^3}$

Comment: As rel. humidities in a room can be higher than 82 % at outdoor temperatures of 15°C, the bar for HCHO in figure 3a and 3b of $\vartheta_o = 15^\circ C$ is calculated by extrapolating the above formula to higher rel. humidities, which may cause uncertainties.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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PAPER 13

AN OVERVIEW OF THE R-2000 HOME PROGRAM DESIGN AND
INSTALLATION GUIDELINES FOR VENTILATION SYSTEMS

MARK RILEY

Chief
Residential Technology and Industry Development
New Housing Division
Energy Conservation Branch
Energy, Mines and Resources Canada
Ottawa
Ontario
K1A 0E4
Canada

SYNOPSIS

This paper outlines the development of guidelines for the design and installation of ventilation systems installed in energy-efficient homes constructed under the R-2000 Home Program of Energy, Mines and Resources Canada. The guidelines represent one of the first initiatives to develop comprehensive requirements for the design and installation of mechanical ventilation systems for residential buildings in Canada. The guidelines outline requirements for a continuous supply of ventilation air to dilute and therefore control contaminants produced from dispersed sources in a home (e.g. occupants and building materials), an additional capability for periods of high humidity or contaminant production. The guidelines also specify that contaminants and odours in kitchens and bathrooms must be removed at their source and exhausted directly to the outside. The ventilation system must be designed and installed so that it does not contribute to an increase in the pressure difference across the building envelope above specified levels. Requirements for providing makeup air, if required, are specified to avoid backdrafting of combustion appliances and reduce the entry of soil gases into the building. Ventilation air must be distributed throughout the house and introduced to occupied zones in manner that does not cause discomfort to occupants.

1.0 INTRODUCTION

The provision of adequate ventilation in residential occupancies can only be assured with positive, reliable mechanical ventilation systems.

The R-2000 Home Program Design and Installation Guidelines for Ventilation Systems [1] requires a mechanical ventilation system be installed to supply a minimum amount of ventilation air, on a continuous basis, of 5 L/s to each habitable room, bathroom and kitchen and 10 L/s to basement areas and utility rooms.

There is a requirement for an additional minimum intermittent capacity of 25 L/s to control excess humidity or contaminants. This shall be activated by means of a humidity controller and by either a manual override or a timer. Procedures for measuring installed airflow rates are specified in the guidelines.

There must also be a capability to exhaust contaminants and odours at their source at a minimum rate of 50 L/s from a kitchen and 25 L/s from each bathroom. This may be achieved by means of individual exhaust units or a central ventilation system.

The ventilation system must be designed and installed so that it does not contribute to a pressure difference across the building envelope of more than 10 pascals (Pa) with continuous ventilation and not more than 20 Pa with intermittent operation.

There are procedures for providing makeup or replacement air to avoid the house exceeding allowable pressure differences. This requirement minimizes the entry of soil gases into the home and backdrafting of any woodburning appliances.

To avoid discomfort to occupants, when the temperature of the ventilation air is lower than that of the indoor air, it must be heated or adequately mixed with the indoor air before being discharged into the occupied zones. Forced warm air heating systems offer a means to heat, mix and distribute ventilation air to the rooms in a house, providing the heating system fan is operated continuously. In buildings with perimeter baseboard or panel heating systems, a means of distribution and introduction of tempered ventilation air must be provided, as well as a means to exhaust indoor stale air. This can be accomplished through a central system or through a combination of individual room units and/or a central system.

Most of this information is now reflected in the R-2000 training and education courses provided through the Canadian Home Builders' Association (CHBA) and the Heating, Refrigeration and Air Conditioning Institute of Canada (HRAI).

2.0 RATIONALE FOR CHANGES TO THE EXISTING GUIDELINES

The new ventilation guidelines were developed in response to a review of the technical requirements for R-2000 homes conducted by the Bureau of Management Consulting [2], and the results of a program of testing and monitoring of the initial R-2000 homes.

During the review of technical requirements, more than seventy individuals across Canada, including builders, mechanical contractors, equipment suppliers and manufacturers, representatives from government housing agencies and utilities, warranty and regulatory authorities and building scientists were surveyed. For the monitoring program, approximately three hundred R-2000 homes and a sample of control homes representing typical construction were monitored to measure levels of various airborne contaminants and to determine the performance of ventilation systems installed in R-2000 homes.

The technical review and the monitoring program identified a number of important issues and concerns which needed to be addressed.

1. Regulatory authorities and building inspectors generally felt that existing ventilation guidelines were too vague and presented difficulties in enforcement and compliance.

2. While the monitoring results showed that, on average, the air quality in the initial R-2000 homes was as good as, or superior to, the air quality in the sample of conventional homes, there was some variation among individual homes [3]. The results indicated a need to ensure that minimum ventilation rates are met in all houses and that ventilation air is distributed to all areas of the house.
3. Most of the individuals surveyed indicated that there was a need for greater flexibility in the types of ventilation systems that could be installed in R-2000 homes. More specifically, it was felt that the existing requirements focused primarily on balanced air-to-air heat recovery ventilators and virtually excluded other types of ventilation systems, including those incorporating simple, inexpensive fans.
4. Concern was expressed that there was no mechanism for accommodating unbalanced ventilation systems, including new heat recovery systems which recover heat from stale exhaust air to heat domestic water.
5. The survey indicated that requiring makeup air for all exhaust equipment, regardless of size or time operated, was too rigid. It was felt that revision of the R-2000 technical requirements to restrict the use of those combustion appliances most susceptible to backdrafting or spillage of combustion products has substantially reduced concern over negative pressures in the house. Some organizations were particularly concerned that the use of recirculating kitchen range hoods was being encouraged, and that clothes dryers were being vented inside the house.
6. The review indicated that the issue of when and how makeup air would be provided to the building was inadequately addressed in the existing guidelines. No guidance was provided on how to size of makeup air ducts.
7. Concern was expressed that some ventilation systems, though installed with sufficient capacity, were not being operated, or were operated infrequently, and therefore were not adequately controlling contaminants. This indicated a need to address the issues of ventilation system controls and operation.
8. There was concern that the existing requirement for a ventilation capacity of 0.5 ach (air changes per hour) was excessive for large homes and the required equipment would be prohibitively expensive to install and operate.

In summary, the review of technical requirements and the monitoring results indicated the need for major revisions to broaden the types of ventilation equipment that can be used and to provide more information and guidance on the design of ventilation air distribution systems, the installation of makeup air inlets and methods of measuring airflows to ensure compliance.

3.0 DEVELOPMENT OF THE NEW GUIDELINES

Consultants were retained to assist Energy, Mines and Resources Canada (EMR) and the Canadian Home Builders' Association (CHBA) in the development of the new ventilation guidelines.

Existing standards formed the basis for developing the new ventilation guidelines. In particular, ASHRAE Standard 62-81, Ventilation for Acceptable Indoor Air Quality [4] was used as the basis for establishing a continuous minimum ventilation rate for each room of the house to control contaminants generated by the occupants and other interior sources such as building materials and furnishings. However, refinements were necessary in order to address a number of issues not covered in this standard, including the supply of ventilation air to basement and utility areas and the need to control excessive humidity and very high levels of contaminants generated on an intermittent basis.

Installation requirements for equipment were based primarily on the Canadian Standards Association (CSA) draft standard for the installation of heat recovery ventilators [5], the Heating, Refrigeration and Air Conditioning Institute of Canada (HRAI) Residential System Design Manual [6] and experience gained during the initial phase of the R-2000 Home Program.

The new guidelines assume that outside air is suitable for ventilation use and therefore no provision is made for filtering or conditioning it. It was felt that it would be very difficult at this time to specify the quality of outside air being used for ventilation and then determine a means of compliance for every home.

The new guidelines do not have specific performance requirements related to noise but do specify that systems should be installed to minimize noise to occupants. It was felt that there was not enough information to develop a formal specification at this time.

The first draft of the new guidelines was sent to the seventy individuals included in the initial survey and to ventilation equipment manufacturers and suppliers, members of the CSA Committee on Installation Guidelines for Heat Recovery Ventilators (CSA Standard C444), some members of the committee responsible for ASHRAE Standard 62-81, and other consultants and researchers. Revisions were made as a result of the comments received, and the revised draft was submitted to the R-2000 Technical Advisory Committee for approval in principle. Editing and refinements followed comments from other industry representatives involved with the implementation of the R-2000 Home Program. The guidelines were then recommended for implementation by the R-2000 Technical Requirements Committee.

4.0 RELATIONSHIP WITH ASHRAE STANDARD 62-81

ASHRAE 62-81 focuses primarily on the control of carbon dioxide and body odour generated by occupants and recommends a minimum ventilation rate of 5 L/s for each habitable room. This rate was adopted as the continuous ventilation rate for general contaminant control in habitable rooms, kitchens and bathrooms.

ASHRAE 62-81 recommendations concerning requirements for the removal of contaminants from kitchens and bathrooms have also been incorporated into the R-2000 ventilation guidelines. Exhaust capacities of 50 L/s and 25 L/s respectively should be installed in these rooms.

ASHRAE 62-81 does not address the issue of ventilation for basement, workshop or utility rooms. These are areas with particular ventilation requirements because of activities carried out and materials stored in them. A continuous ventilation rate of 10 L/s for these areas was proposed and met with acceptance. This requirement has the added advantage of allowing subsequent finishing of the basement as two habitable rooms without requiring modification of the ventilation system capacity. Utility rooms are defined as areas that are entered and where activities are carried out, such as laundry rooms and workshops, but exclude areas such as closets, storage rooms, mechanical rooms and furnace rooms with a combustion air supply.

ASHRAE 62-81 also does not address the issue of controlling excess humidity or higher-than-normal levels of contaminants generated on a short-term basis. This was felt to be an important issue since excessive humidity can increase the risk of damage to the building envelope or result in condensation, mould and mildew within the building. The R-2000 ventilation guidelines therefore include a requirement for additional intermittent capacity of 25 L/s, to be activated manually or by a humidity controller.

The program also had to address the issue of large open areas which comprise more than one functional room, such as a combined living/dining-room area. The guidelines specify that these areas should be treated as two individual rooms. Some judgement and interpretation will be needed in order to determine whether a particular area should be considered as one or more rooms. For example, a small eating area in a kitchen would not be regarded as a separate room. Table 1 provides an example of the ventilation requirements for a typical dwelling unit.

The continuous ventilation air for kitchens, bathrooms, basement and utility rooms can be provided indirectly by increasing the amount of ventilation air to other rooms provided that air is continuously exhausted from these rooms at the required rate.

The exhaust capability for the kitchen and bathrooms can be met with a central balanced system exhausting air from the kitchen and bathrooms or by providing separate manually operated exhaust equipment in the kitchen and bathrooms.

TABLE 1

VENTILATION REQUIREMENTS FOR A TYPICAL DWELLING

	Continuous L/s	Exhaust Capability L/s
Kitchen	5	50
Dining Room	5	
Living room	5	
Bathroom #1	5	25
Bathroom #2	5	25
Master Bedroom	5	
Bedroom #2	5	
Bedroom #3	5	
Basement	10	
Intermittent Capacity	25	
Total System Capacity	75	

Table 2 presents a possible distribution arrangement for the typical dwelling unit using a central balanced ventilation system such as a heat recovery ventilator and one additional bathroom fan as illustrated in Figure 1.

TABLE 2

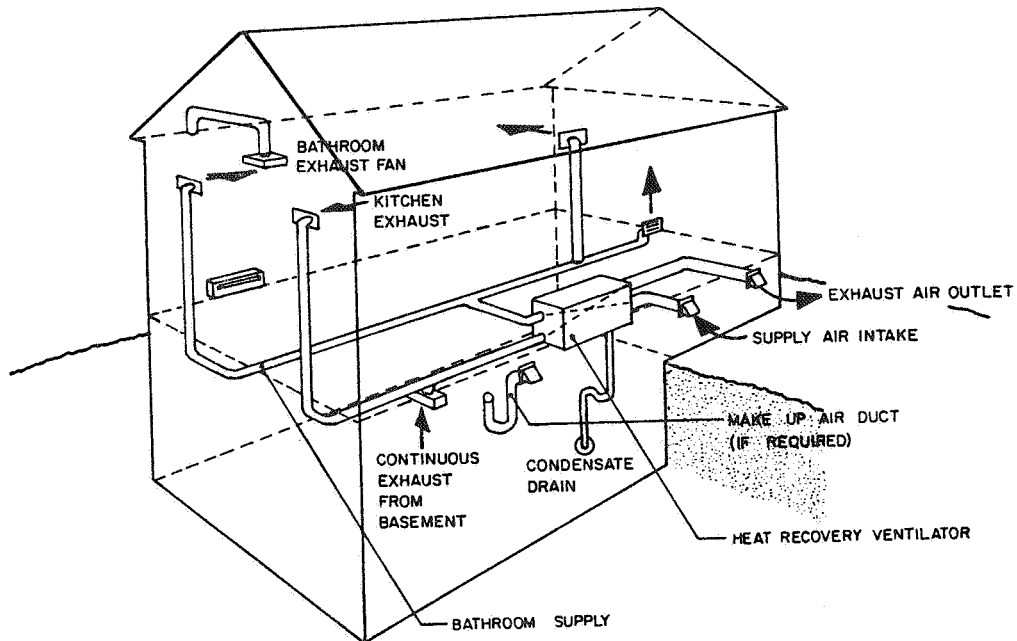
DISTRIBUTION ARRANGEMENT USING A CENTRAL BALANCED VENTILATION SYSTEM AND A SEPARATE BATHROOM FAN

	Central System Supply L/s	Exhaust L/s	Separate Exhaust L/s
Kitchen		50	
Dining Room	10		
Living room	15		
Bathroom #1		25	
Bathroom #2	10		25
Master Bedroom	10		
Bedroom #2	10		
Bedroom #3	10		
Basement	10		
Total	75	75	

The ventilation system would be set at 50 L/s to provide continuous ventilation (low-speed). Where this rate is greater than 0.45 ach, the installer is permitted to reduce the continuous ventilation rate setting to the equivalent of 0.45 ach. The maximum capacity at 75 L/s would be activated by a humidity controller or by a manual switch or timer. The bathroom fan would be activated by a manual switch or timer.

FIGURE 1

POSSIBLE DISTRIBUTION ARRANGEMENT USING BY A HEAT RECOVERY VENTILATOR AND SEPARATE BATHROOM EXHAUST FAN



5.0 VENTILATION BASED ON NUMBER OF ROOMS INSTEAD OF HOUSE VOLUME

It is felt that using the number of rooms in the house as the basis for calculating the ventilation requirements has clear advantages over using the house volume. A calculation based on the number of rooms provides a relatively simple method for builders and installers to determine ventilation requirements and for inspectors to verify compliance of a ventilation system.

A calculation based on the interior volume of a house is particularly dependent on the foundation type and size of the rooms. The amount of ventilation air provided to the house could vary greatly depending on whether the house is constructed with a slab-on-grade, crawl-space or full basement foundation or whether rooms have cathedral ceilings.

The issue of distributing ventilation air is also addressed by the use of a per-room requirement. The guidelines state that the amount of ventilation air provided to each room must not be less than the per-room requirement specified in the guidelines.

The per-room requirement ensures that a minimum amount of ventilation air is supplied to the occupied zone of each room regardless of the overall construction of the house or size of room. Ventilation rates in R-2000 homes would typically range from 0.30 to 0.45 ach. The average ventilation rate for R-2000 homes built to date is equivalent to 0.35 ach [3].

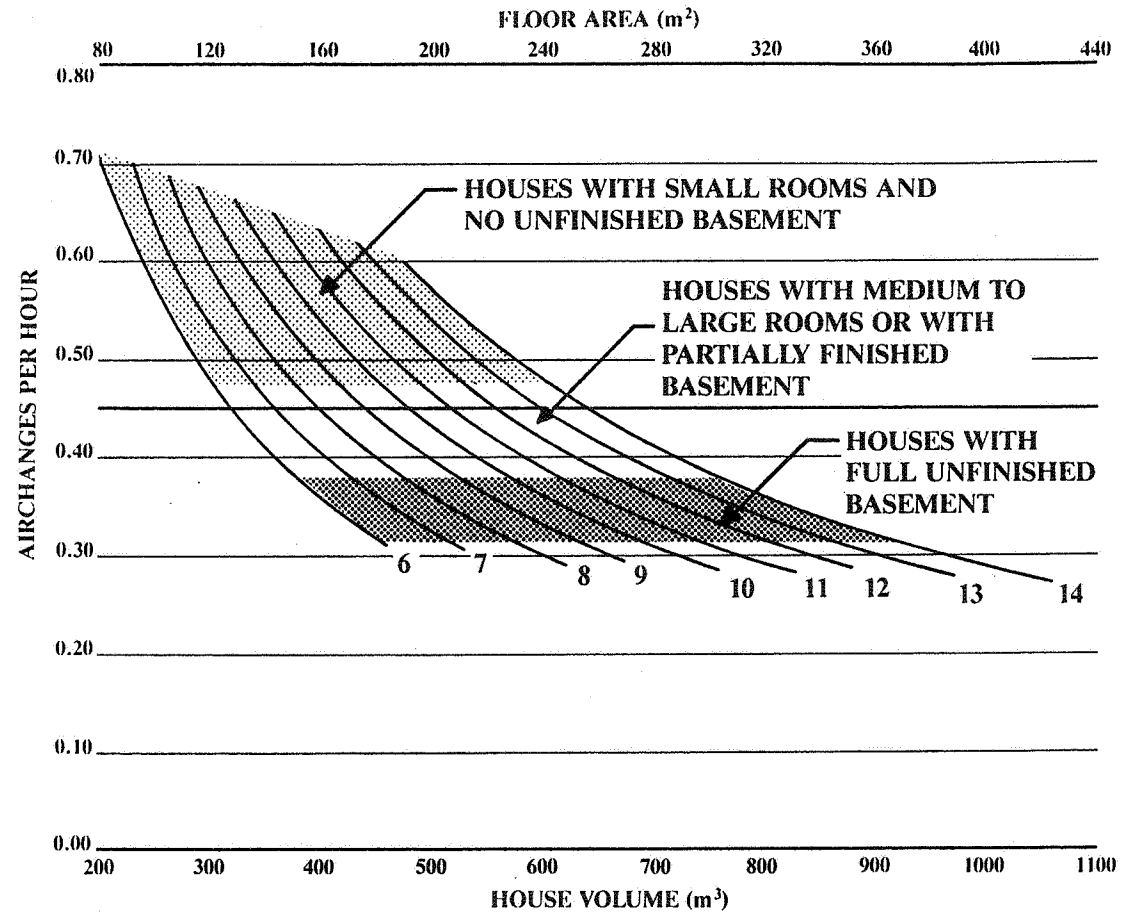
The relationship between the ventilation rate calculated by the per-room method and house volume is illustrated in Figure 2. For example, a small bungalow with a slab-on-grade foundation would have a volume of about 300 m³. The ventilation rate, depending on the number of rooms, could be equivalent to an air change rate in excess of 0.5 ach. The same house with a full basement would have twice the volume and therefore have a ventilation rate equivalent to 0.30 ach.

Concern was expressed that the air change rate achieved in some houses, particularly those with small rooms and a slab-on-grade foundation or a fully finished basement, could be excessive for some types of occupancy. Therefore the continuous ventilation rate can be adjusted downwards to be equal to an air change rate of 0.45 ach. However, the installed system must be still be capable of providing the total unadjusted capacity required to meet the minimum rate specified by the per-room calculation. It should be noted that this reduction is generally small in terms of actual airflow. For example, if a small slab-on-grade bungalow has seven rooms and a utility room, the per-room calculation specifies a ventilation rate of 45 L/s. This is equivalent to 0.54 ach if the house volume is 300 m³. Adjusting the continuous ventilation rate to the equivalent of 0.45 ach reduces the required flow rate to 37.5 L/s and does not include an estimated 0.05 ach of natural infiltration for R-2000 homes.

Provisions in the guidelines allow kitchens, bathrooms, utility areas and basements to be ventilated indirectly with air supplied from another room. This can be used to advantage in designing a ventilation system or to increase ventilation to certain rooms without increasing the overall ventilation rate. For example, ventilation air for kitchens and/or bathrooms can be provided via living rooms and bedrooms, providing stale air is being exhausted from the kitchens and bathrooms at the ventilation rate specified for those rooms. This permits the use of balanced ventilation equipment such as an HRV to supply air directly to some rooms while exhausting air from others to meet all ventilation requirements.

ASHRAE is now considering revising Standard 62-81 and basing the ventilation rate on house volume. The proposed rate of 0.35 ach reflects average air change rates monitored in the initial R-2000 demonstration homes [3] and is equivalent to the average ventilation rate for these homes calculated by the per-room procedure specified in the new R-2000 guidelines. The proposed revision to the ASHRAE standard is at the draft stage. It should be noted that the Canadian Standards Association draft national standard for residential ventilation is based on a per-room requirement similar to the R-2000 guidelines.

FIGURE 2. AIR CHANGE RATES FOR HOUSES CONFORMING TO THE NEW GUIDELINES



6.0 MAXIMUM PRESSURE DIFFERENCE ACROSS THE BUILDING ENVELOPE

The R-2000 ventilation guidelines no longer include a specific requirement for balanced airflows for ventilation systems. This issue is addressed by specifying maximum allowable pressure differences between the interior and the exterior of the building envelope rather than balanced airflows. This will permit the installation of a wide range of ventilation equipment including exhaust-air heat pump heat recovery systems that are not designed to operate with balanced airflows. These can now be installed in R-2000 homes provided excessive pressure differences are not created across the building envelope.

Concern about the consequences of negative pressure in the building has been reduced, since the new R-2000 Technical Requirements do not allow the installation of naturally aspirating combustion appliances for space and water heating. They also specify that only well-designed fireplaces and wood stoves with sealed doors and a separate supply of outside air directly to the firebox can be installed.

However, there remains some concern about the impact of very high negative pressures across the building envelope on the operation of combustion appliances and, in some areas, about the entry of soil gases into the house. Therefore, the ventilation guidelines have set limits for the maximum pressure difference allowed across the building envelope.

The guidelines specify an allowable pressure difference of 10 pascals (Pa) during continuous operation of the ventilation system and 20 Pa during the intermittent operation of any individual equipment or single appliance while operating simultaneously with continuous operation of the ventilation system. For example, an HRV with supply fan shut down for defrost or a kitchen exhaust fan might represent the largest intermittent unbalanced airflow in a house. In either case, only the single device with the largest unbalanced airflow is considered, since the standard assumes that exhaust devices would rarely operate simultaneously.

The allowable pressure differences are significantly higher than those which would be considered for conventional homes, where naturally aspirating combustion appliances and open fireplaces are permitted. The CSA draft residential ventilation requirements standard [7] suggests an allowable pressure difference of only 5 Pa to minimize backdrafting problems in these homes.

Further monitoring is required to determine whether further restrictions are necessary for those areas with high radon concentrations. To date, radon levels have been low in most R-2000 homes across Canada.

7.0 PROVISION OF MAKEUP AIR

Unbalanced ventilation airflow will cause a change in the pressure difference across the building envelope. The magnitude of this change will be determined by the magnitude of the unbalanced airflow and the air leakage characteristics of the building envelope. Where unbalanced airflows are large and/or when air leakage through the building envelope is small, excessive pressure differences could develop unless makeup air from the exterior is provided. It was therefore necessary to provide procedures for identifying cases where makeup air would be required and for determining the number and size of makeup air inlets [8].

Appendix A of the guidelines describes three methods by which program authorities and builders can determine compliance with the pressure difference limits specified in the guideline. These methods were formulated with the intention of avoiding the need for expensive additional tests on the building and providing the flexibility to determining compliance at both the design and/or post-construction stages.

Manufacturers' specifications for airflow rates for ventilation fans and other air-exhaust equipment, when tested to recognized standards such as Ashrae 51-75 or CSA C260.2-1976, were accepted as a means to determine maximum airflows without the need to measure airflows for all ventilation and air exhaust equipment installed in homes. In most cases, only the minimum continuous ventilation rate must be confirmed by measurement.

The envelope air leakage characteristics, as determined by the fan depressurization test [9] performed for all R-2000 homes, was recognized as suitable source of information for determining compliance with the requirement that unbalanced airflows do not result in pressure differences across the building envelope exceeding permissible limits.

This method uses the Equivalent Leakage Area (ELA) of the building envelope, obtained by means of the fan depressurization test, to determine compliance. The ELA is the sum of all the unintentional openings in a building envelope. A chart has been developed which gives the relationship between the building ELA and the maximum allowable unbalanced airflow to cause a 10 or 20 Pa pressure difference across the building envelope, based on the typical characteristics of R-2000 homes. For buildings where the ELA is insufficient to limit pressure differences to 10 or 20 Pascals, Table 3 was developed which gives the additional ELA that can be provided by installing makeup air inlet ducts of different sizes. Duct sizes are based on an effective duct length of 25 m.

TABLE 3

**EQUIVALENT LEAKAGE AREA (ELA) PROVIDED BY
INLET DUCTS OF VARIOUS DIAMETERS**

DUCT DIAMETER		ELA PROVIDED
mm	(in.)	(m ²)
75	(3)	0.0024
100	(4)	0.0052
125	(5)	0.0092
150	(6)	0.0156
175	(7)	0.0240
200	(8)	0.0340

A second option involves determining at the design stage, the size of makeup air inlet which will provide enough makeup air to limit pressure differences caused by unbalanced airflows for those cases where fan depressurization test data are not known or where the builder wishes to design for the worst case. A table was developed, Table 4, which indicates the size of makeup air inlet ducts required for limiting pressures differences to 10 and 20 Pa for various unbalanced airflows. This table assumes a minimal amount of leakage through the building envelope. Duct sizes are also based on an effective duct length of 25 m (75 ft).

TABLE 4

**SIZE OF MAKEUP AIR INLET DUCTS WHERE THE EQUIVALENT
LEAKAGE AREA OF THE BUILDING ENVELOPE IS NOT KNOWN**

Unbalanced Airflow		Required Makeup Air Inlet
Continuous L/s (cfm)	Intermittent L/s (cfm)	Duct Diameter mm (in.)
10 (20)	20 (40)	75 (3)
20 (40)	30 (60)	100 (4)
30 (60)	50 (100)	125 (5)
50 (100)	80 (160)	150 (6)
75 (150)	125 (250)	175 (7)
100 (200)	170 (340)	200 (8)

The third method determines compliance by means of a test to measure pressure differences across the building envelope. This test is normally only used for borderline cases, since the ELA of a building, as determined by the fan depressurization test, can be directly related to the maximum allowable unbalanced airflow at 10 or 20 Pa. The instruments required for this test are the same as those used for measuring continuous ventilation rates in homes.

To assist builders at the design stage, a routine in the R-2000 energy analysis program (HOT-2000) estimates the ELA of the house and the allowable unbalanced airflow at 10 or 20 Pa pressure difference before makeup air would be required. This is based on fan depressurization test results from 250 R-2000 homes.

Experience with existing R-2000 homes has shown that the average R-2000 Home would require a makeup air inlet when unbalanced airflow exceeds 50 L/s for continuous operation and 70 L/s for intermittent operation.

It should be noted that there are separate codes and requirements for the supply of outside air for combustion to all fuel-fired space and water heating equipment, including wood-burning appliances such as fireplaces. Therefore the ventilation guidelines do not provide information on combustion air inlet requirements for combustion equipment, nor can combustion air be used as makeup air for unbalanced ventilation equipment. The supply of combustion air for fuel-fired appliances is a separate requirement from supplying makeup air for ventilation equipment to control pressures differences across the building envelope.

8.0 COMPLIANCE WITH VENTILATION REQUIREMENTS

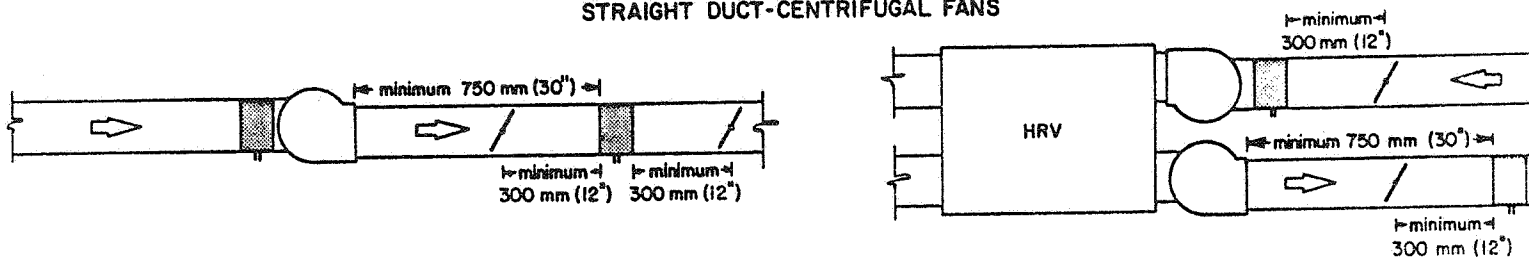
For compliance and inspection purposes, the guidelines require that flow-measuring devices or sensors be permanently installed in the supply and/or exhaust ducts of the mechanical ventilation system in locations that allow the continuous ventilation rate to be accurately measured. The sensors will also permit inspectors to quickly verify that required airflows are being provided and will allow airflows to be checked simply and inexpensively during service visits.

Appendix B of the guidelines gives information on locating and installing sensors in ductwork as illustrated in Figure 3 and procedures to measure airflows accurately.

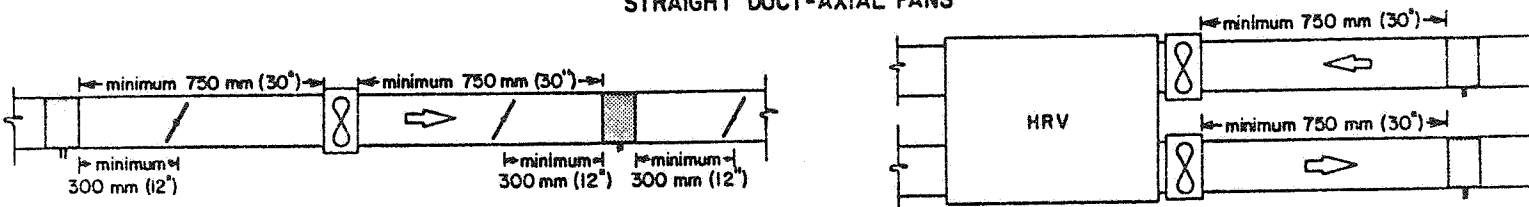
Where kitchen and bathroom fans are used for intermittent ventilation, the rated capacity would normally be accepted, though it is recognized that the actual installed airflows could be lower than those specified. The issue of installed airflows which are lower than rated airflows will be addressed in planned revisions to existing standards governing the rating of fans and ventilators. Where the installation appears to be deficient, an inspector may wish to have confirmation that the installation meets the intent of the requirements.

The guidelines also specify that a report must be completed by a certified installing contractor stating that the ventilation requirements have been met.

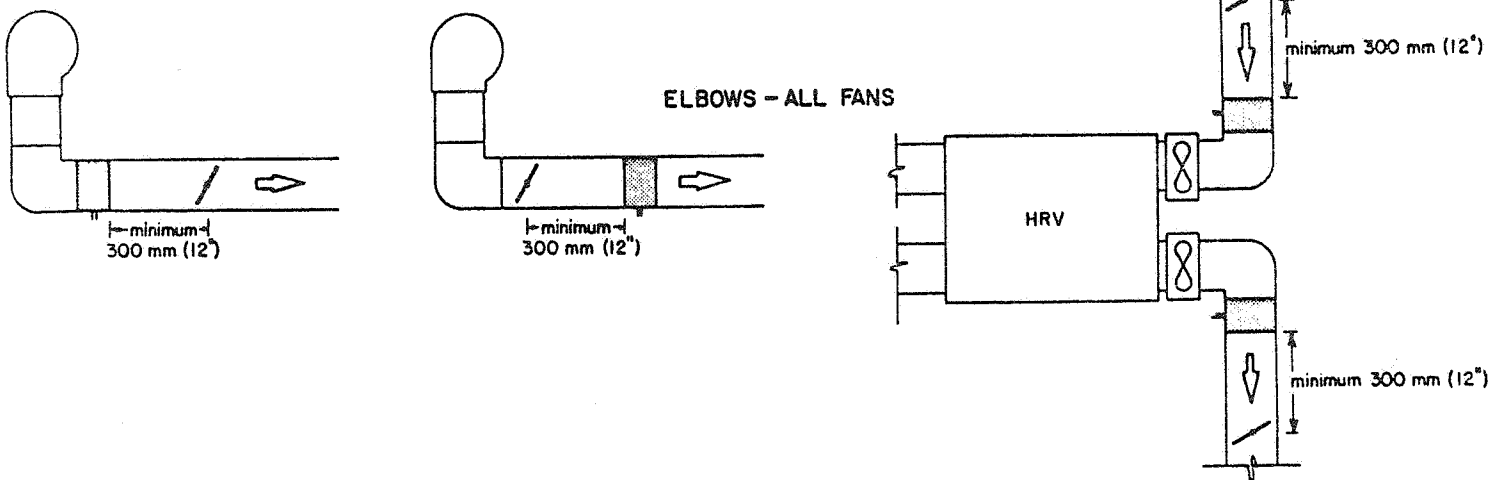
STRAIGHT DUCT-CENTRIFUGAL FANS



STRAIGHT DUCT-AXIAL FANS



ELBOWS - ALL FANS



LOCATION OF AIRFLOW MEASURING STATIONS

FIGURE 3

9.0 ACCEPTABLE VENTILATION SYSTEM CONFIGURATIONS

The guidelines specify the ventilation performance to be achieved rather than prescribe certain configurations. In many houses a single central system, such as an HRV, is able to meet all the ventilation requirements. In others it may be desirable to use more than one component. For example, separate fans can be used to meet specific intermittent exhaust requirements when it is difficult to exhaust through a central system or when there is insufficient capacity to meet program requirements.

The guidelines require that each room in the house be supplied with ventilating air. This can be achieved by a separate ducted ventilation system or by an existing forced-air heating system providing it is designed to circulate air continuously throughout the house.

The guidelines also permit an installer to use dampers in the duct work or other airflow control devices to switch the same airflow used for intermittent exhaust between different bathrooms when there is insufficient capacity to meet all intermittent exhaust requirements simultaneously.

Since the guidelines allow kitchens, bathrooms, utility areas and basements to be ventilated indirectly with air supplied via another room, the builder can increase the supply of ventilation air to such areas as living rooms and bedrooms to more than the minimum of 5 L/s, while exhausting stale air from kitchens and/or bathrooms. This permits the effective use of balanced ventilation equipment, such as HRVs, to supply ventilation air directly to some rooms while exhausting stale air from other rooms.

While a balanced heat recovery ventilator (HRV) is still viewed as an effective means of meeting the R-2000 energy consumption target, alternative approaches, such as recovering heat from stale exhaust air for domestic water heating, can now be used. For homes with high levels of insulation which use particularly energy-efficient heating systems such as heat pumps, the ventilation requirements could be met by one or more conventional exhaust fans, providing the R-2000 energy consumption target is achieved. Appendix C of the guidelines provides illustrated examples of suitable ventilation system configurations.

10.0 CONCLUSIONS

The new R-2000 Ventilation Guidelines are the most comprehensive requirements developed to date for the ventilation of residential buildings in Canada. They attempt to address a wide range of issues related to air quality and the design, installation and compliance of ventilation systems.

The types of balanced ventilation systems with heat recovery which have become commonplace in R-2000 homes remain attractive and allowable under the new ventilation guidelines but a far greater range of design possibilities has been opened up for builders.

Although the guidelines represent a major milestone, further work is underway to develop and refine national consensus standards for ventilation requirements and equipment. Experience gained from the use of the new guidelines and data gathered from an ongoing monitoring and evaluation program will determine whether any refinements will be necessary in the future.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contribution of Mark Lawton and Paul Duffy of Buchan, Lawton, Parent Ltd. and Gustav Handegord of Trow Ltd. in the development of the ventilation guidelines and the preparation of this report.

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PAPER 14

DESIGN, CONSTRUCTION AND PERFORMANCE
OF A DYNAMIC WALL HOUSE

J. TIMUSK

Professor
Department of Civil Engineering and
Chairman
Centre for Building Science
University of Toronto
Toronto
Ontario
M5S 1A4
Canada

SYNOPSIS

The construction and performance of a dynamic wall house are described. It is suggested that such houses function much like the traditional houses with leaky walls and active chimneys. Only here ventilation is controlled while a significant part of the energy required to heat the ventilation air can be recovered from part of the conducted heat which would otherwise be lost. A model is proposed to explain how such walls function at relatively low ventilation rates. This approach promises to improve indoor air quality and thermal envelope performance at reduced construction and energy costs.

1. OLDER HOUSES

Older houses were virtually free from indoor air quality and moisture problems because of the combination of a relatively leaky thermal envelope and an active chimney. The volume of air moved through the house was more than adequate to dilute moisture and contaminants from the building interior. Not only was much of the spent air exhausted harmlessly through the chimney, but also the resulting depressurization counteracted positive pressures due to stack and wind to reduce exfiltration through the envelope and associated concealed condensation in walls and attic space.

The raising of the neutral pressure plane by the active chimney also led to infiltration through a larger portion of the thermal envelope, assuring a supply of ventilation air to all of the rooms with exterior walls. In a cold climate, such as that in Canada, low indoor relative humidity was the heating season indoor air quality problem.

The major drawback of the above approach was of course excessive energy consumption: heat could not be recovered from the spent air which was exhausted through the chimney and which exfiltrated through the thermal envelope. Also, the process was largely uncontrolled because total leakage opening area, leakage opening distribution and the pressure across the envelope to drive air leakage were not controlled.

In summary, older houses performed well with respect to air quality and moisture problems because the active chimney exhausted spent air, imposing in the process a negative pressure on the enclosure. They could be classified as negative-pressure houses.

2. THE NEGATIVE PRESSURE HOUSE

The shortcomings of the chimney-vented, leaky house can be largely avoided if the following is done.

1. The chimney is replaced with an exhaust fan. The fan can now be operated as needed, exhausting air at a controlled rate. Heat from the exhaust air can, in turn, be recovered with a heat pump. If the recovered heat is transferred to domestic hot water, the efficiency of the heat pump is improved because heat is recovered from the air stream which is at room temperature. Continuous operation of the ventilation system is now virtually guaranteed as ventilation is coupled to domestic hot water, which is a necessity.

2. The total envelope leakage area is controlled. Exfiltration can be completely eliminated if the envelope is made sufficiently airtight so that the negative pressure arising from the exhaust of spent air at the prescribed ventilation rate overpowers positive pressures due to wind and stack action.

When air-to-air heat exchangers are used, heat can only be recovered from air exhausted through it. Here the building enclosures have to be built airtight since heat cannot be recovered from exfiltrating air. Wind, stack and unbalanced fan pressures drive such exfiltration.

In the exhaust-only approach, on the other hand, pressure is controlled, which means that all of the air leakage openings need not be eliminated. As long as the exhaust rate is sufficient to overpower positive wind and stack pressures, no heat is lost with exfiltrating air. Moisture damage due to the condensation of moisture from exfiltrating air can also not occur. Performance now becomes less dependent on workmanship.

3. Air leakage openings are uniformly distributed. This way ventilation air is supplied uniformly through all of the walls, provided that pressure distribution across the walls is also reasonably uniform. As room volume is more or less proportional to exterior wall area, the air change rate in all the rooms then tends to become uniform. In other words, ventilation air is evenly distributed throughout the house without having to resort to an internal air circulation system.

An air barrier made with an air-permeable membrane will make it possible to minimize air leakage through larger openings while providing a controlled flow over the entire air barrier.

4. The wall is built as a dynamic wall. Once the above three requirements have been satisfied, it is a relatively simple matter to build a wall which also acts as a heat exchanger, transferring conducted heat entering the wall to the incoming ventilation air stream. In the following the heat and mass transfer mechanisms in a dynamic wall will be considered.

3. THE DYNAMIC WALL

The dynamic insulation and wall concepts are not new. They were first proposed in Sweden by Torgny Thoren¹. The possibilities of recovering conducted heat to preheat ventilation air, to capture solar heat, to control moisture damage and to improve indoor air quality were recognized. An experimental dynamic wall house was also built in Sweden in 1978 but "in spite of good indoor climate the energy goals were not satisfied."² In a theoretical treatment of heat and mass transfer through dynamic insulation Anderlind and Johansson developed a heat transfer model where the temperature gradient in dynamic insulation becomes curved and where the overall wall temperature is lowered.³

It often happens that new concepts have to wait for the development of new materials before they can be put into practice. This appears to be the case with dynamic insulation; a material had to be developed which makes it possible to provide the required control of air entering the dynamic insulation. It has to, however, be added and that it is still not generally understood how such walls actually function.

The author's work on dynamic insulation came about as an afterthought. Earlier work on moisture problems had suggested that relatively minor changes to the design of wood frame house walls could significantly improve their performance. For example, by locating a moisture-permeable air barrier on the outer face of the wall insulation, it becomes easier to install and to inspect because it is not penetrated by partition walls, joist assemblies and electrical wires. The exterior air barrier will also prevent wind from blowing through air permeable insulation and, in the process, cooling the wall. Also, a more uniform room-side wall surface temperature would result if insulating sheathing is used to blunt the thermal bridges formed by the framing members.

The introduction to the market of a spunbonded polyolephin (SBPO) sheet-covered glass fibre insulating sheathing board and special tape for joining the boards to each other and to window and door frame made it practical to evaluate the above concept in a house the author was building. The SBPO membrane is for all practical purposes air and watertight, yet sufficiently water vapour permeable so that it can be located on the cold side of the insulation. Its air permeability is of just the right magnitude required for the air flow control membrane of a dynamic wall.

Air leakage tests conducted on the partially completed house a year after the building had been closed in showed that not only did the house with the SBPO air barrier for its walls meet the Canadian R-2000 Low Energy housing program envelope airtightness requirements, but the thermal envelope was sufficiently air permeable to allow all the ASHRAE Standard 62-81 and the Canadian R-2000 specified ventilation air to be drawn in uniformly through the building walls at a moderate negative pressure of about 10 Pa.

Calculation indicated that of the 1.56 air changes per hour at 50 Pa, 0.9 ACH was through the SBPO membrane. In effect, more than half of the air infiltration was by diffusion through the air barrier, which is an essential feature of a dynamic wall. The walls were then completed as dynamic walls.

Before the house wall designs and performance results are presented, an attempt will be made to examine the heat and mass transfer process in such a wall. The model presented here is limited to a narrow set of conditions and is tentative at best. Much needs to be done to completely model the process. In the meanwhile, it is presented to encourage critical discussion.

4. THE HEAT AND MASS TRANSFER MODEL

The purpose of the following is to examine the effect of an air stream moving through glass fibre insulation in a sense opposite to that of heat flow on wall temperature distribution and the associated energy balance. Of these the former has to do with the physical performance of the wall and the associated thermal comfort while the latter concerns energy saving possibilities.

A rather narrow set of conditions will be dealt with: where outdoor and room temperature remain constant, where solar radiation is negligible and where the rate of air movement through the wall is equal to or less than the optimum rate. Optimum is with reference to a conventional no-air-flow or "static" wall, where the rate of heat flow into the dynamic wall is equal to that of the static wall. In other words, it is proposed that at low air flow rates the temperature gradient of a dynamic wall is the same as that of its "static" counterpart.

If the temperature gradient through the walls remains unchanged, so does the rate at which heat is transferred through the wall by radiation and by conduction through the solid components of the wall. In the case of glass fibre insulation, the amount of heat conducted through the fibres is very small because the majority of fibres are oriented in a direction parallel to the plane of the wall.

Heat transport through the still air between the fibres of the insulation can be examined on the molecular level. As a result of random molecular motion molecules moving toward the cold side of the wall generally carry more kinetic energy than those moving toward the warm side; the net velocity in still air is however zero.

The ability of a gas to transfer heat, expressed by its coefficient of thermal conductivity, depends on the specific heat of its molecules, the mass density of the gas, the average velocity of its molecules and the mean free path between collisions. To see how this process can be stalled, one can picture molecule 1 of the gas move through one mean free path in the direction of

the temperature gradient and collide with molecule 2 and in the process transfer its energy to molecule 2. In a static wall this molecule-to-molecule transfer process would continue until the heat carried per molecule has traversed the thickness of insulation.

If a flux of air is moved through the insulation in a direction opposite to heat transfer so that when molecule 1 has transferred its energy to molecule 2, molecule 2 is moved with the flux of air to the position originally occupied by molecule 1. After a sufficient number of repetitions of this process molecule 2 will emerge from the warm side of the insulation, having moved in steps of one mean free path, acquiring additional energy from molecule 1 at the end of each move. In effect, all the heat entering the wall and transmitted by conduction through the still air is used to heat the incoming air so that its temperature follows the static wall temperature gradient.

In the above heat and mass transfer process the mechanisms by which heat is transferred in the gas has not changed; only now it is occurring within a moving air mass. The only effect the glass fibres have on the process is to avoid the formation of convective loops in the air stream. There is no transfer of heat from the fibres to the air or vice versa as their temperatures do not differ at any point within the insulation.

It could be argued that only a very small increase in the slope of the temperature gradient through the air film and the gypsum wall board would be sufficient to result in a relatively large increase in the rate at which heat enters the wall. This could however not occur since there would be nowhere for the additional heat to go once the insulation is reached. The slope of the remaining part of the temperature gradient through the insulation would have been decreased so that the rate of radiant and conductive heat transfer through the glass fibres would be decreased. The incoming air could not absorb any of the extra heat because it is already at the interface temperature. Nor could the rate at which heat is conducted through the air be increased because it is fixed by the coefficient of thermal conductivity of air.

As the temperature gradient has not changed, then the rate of conductive heat flow through the glass fibres and the rate of radiant heat transfer will not have changed. As far as the rate of heat leaving the wall is concerned, the wall behaves as if the k-value of the insulation had been decreased by 0.025 W/mK, the value for still air. The rate at which heat enters the wall will still be indicated by the conventional k-value of the insulation.

What has been described above is a 100 per cent efficient heat exchanger. It has no solid component and film resistances to retard heat transfer from one working fluid to another. The role of the glass fibres is passive: to assure laminar air flow and to resist radiant heat transfer.

4.1 The Optimum Air Flow Velocity

Optimum velocity is defined here as the velocity of ventilation air through the insulation at which all the heat conducted through the still air in static insulation is transferred to the ventilation air.

The heat transferred through the still-air phase in our wall comprising glass fibres insulation only is given by:

$$Q = (k/d) A (t_i - t_o) \quad (1)$$

where

Q = conductive heat flow rate through air in the insulation, W

k = coefficient of thermal conductivity of still air, 0.025 W/mK

d = thickness of insulating layer, m

t_i = temperature at the insulation-wall board interface, °C

t_o = temperature at the outside surface of the insulation, °C

The rate at which heat has to be supplied to the incoming air stream to heat it from t_o to t_i is given by:

$$Q = q \rho c_p (t_i - t_o) \quad (2)$$

where

Q = rate of heat absorption by the incoming air to heat it by $(t_i - t_o)$, W

q = rate of air flow through the wall, m³/s

ρ = density of air, kg/m³

c_p = specific heat of dry air, J/kg.

At the optimum rate the still air component of the conductive heat flow entering the wall is equal to the rate of heat supply to the incoming air mass to heat it to inside temperature. Equating the two equations yields the equation for dynamic air flow:

$$q = (k/\rho c_p) \cdot (A/d) \quad (3)$$

This equation gives the optimum or maximum "free" ventilation rate in cubic metres per second. Even in the idealized model this ventilation air is not quite free in that it enters the room at the insulation/wall-board interface temperature. Purchased heat would have to be spent to bring it to room temperature. The first term in brackets gives the diffusivity of air while the second term relates to the physical dimensions of the wall. At ventilation rates which are equal to or less than q , the temperature gradient remains linear, there is no cooling of the wall surface and the ventilation air enters at the insulation-wall board interface temperature. As expected, the temperature difference across the insulation does not appear in Equation 3.

When the optimum rate is exceeded, the rate at which heat can be transferred through air is not sufficient to heat up the air to the static wall temperature gradient. The wall surface now becomes cooled while the air stream also starts to absorb some of the radiant heat. Eventually the temperature gradient at the exterior face of the insulation becomes horizontal, indicating that no heat, radiant or conducted, escapes from the wall. While such flow rates could be justified because of the energy conserved, the associated cooling of the wall surfaces may not be acceptable.

The above is in agreement with measured temperature gradients by Jönsson and presented by Anderlind and Johansson³. Here at the lowest ventilation rate of 1.1 cubic metres per hour for a 150 mm thick layer of insulation the temperature gradient has become nearly linear, even though this rate is still more than twice the optimum value according to Equation 3.

5. DYNAMIC WALL DESIGN

According to Equation 3 the choice of variables is rather limited. Wall area is fixed by other considerations which leaves the thickness of insulation and the choice of dynamic air flow rate to the discretion of the designer and of these only one is an independent variable.

In the case of the author's house, the thickness of insulation was established by the thickness of framing lumber and the decision to use insulating sheathing. With a wall area of 138 m² and 127 mm of insulation the optimum flow rate would yield 0.26 ACH whereas the specified rate is 0.46 ACH. This would result in energy savings of 2240 kWh in a climate with a 4350 k-day heating requirement.

The above suggests that relatively little additional expenditure to build a dynamic wall can be justified purely on financial grounds. Tradeoffs such as the elimination of internal air circulation systems, additional energy recovery from solar radiation and exhaust-air heat recovery could change this.

6. PERFORMANCE EVALUATION OF THE DYNAMIC WALL HOUSE

6.1 House Details

The two-storey wood frame house faces south and is surrounded by open fields. Except for some shielding provided by a sparse pine hedge on the east side and one some distance away from the house on the west side, the house can be considered to be located in open terrain.

An expanded section through the wall, in Figure 1, shows the wall construction. It comprises: 12.5 mm gypsum board, 0.05 mm vapour retarder, 38 x 89 mm wood-frame wall filled with glass fibre batt insulation, 38 mm glass fibre insulating sheathing covered with a SBPO air barrier and 25 x 200 mm rough-sawn pine board and batten siding.

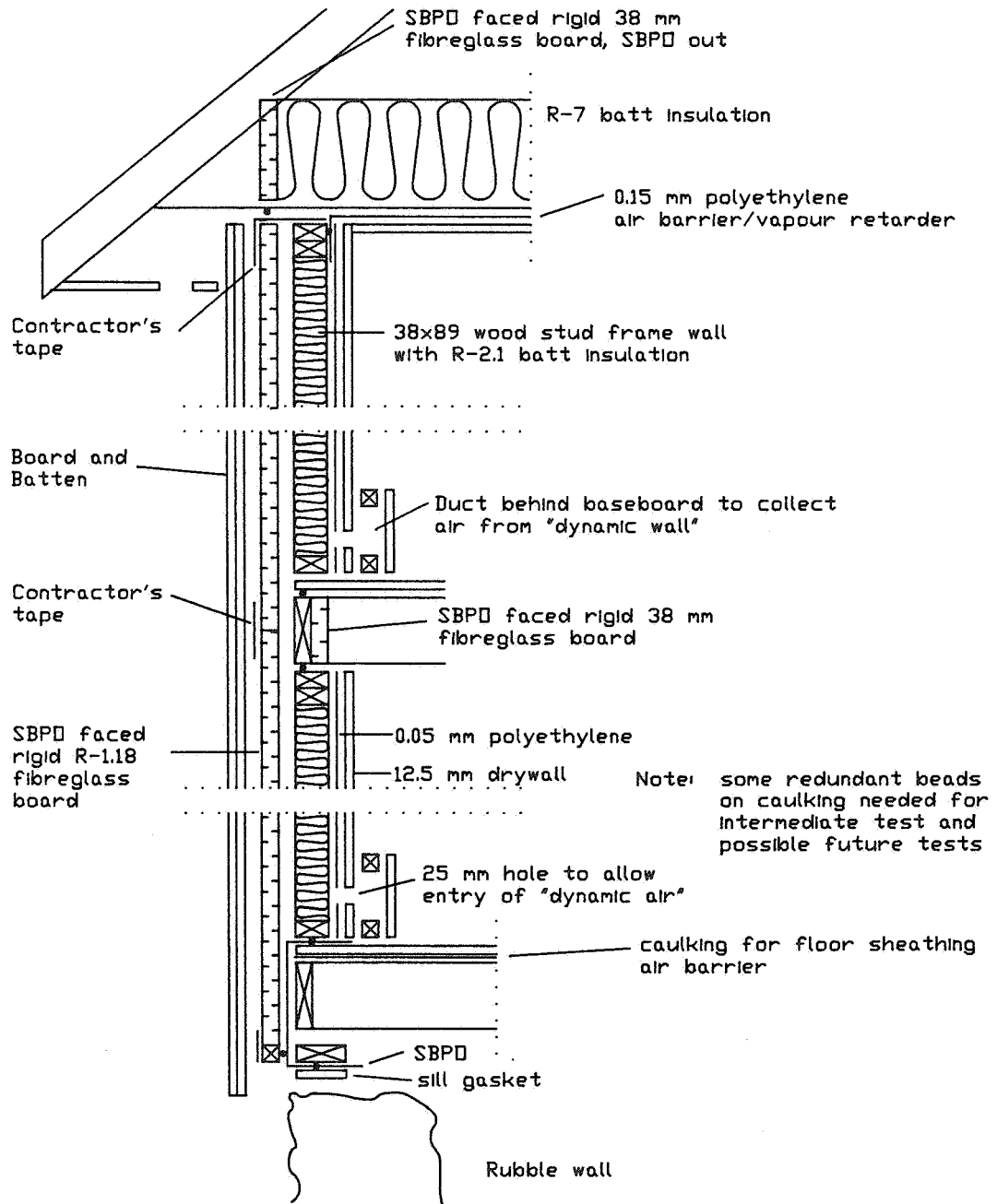


Figure 1. Expanded section through the thermal envelope of the dynamic wall house.

The wall air barrier, perhaps more appropriately the air retarder, is formed by a SBPO membrane attached to individual insulating sheathing boards. Commercially available sheathing tape, specially manufactured for the purpose, is used to provide air barrier continuity with door and window frame, the first storey floor and second storey ceiling air barriers (see Fig. 1). The SBPO membrane also performs the functions of sheathing paper to prevent rain penetration and, for the dynamic wall, the control of ventilation air flow.

The second storey ceiling air barrier is formed by 0.15 mm polyethylene sheet. Acoustical sealant is used to make it continuous at lapped joints. The first storey floor completes the thermal envelope air barrier. It comprises tongue and groove plywood sheathing with acoustical sealant between the floor joists and the floor sheathing. Access to the unheated basement was provided through a gasketed hatch which was screwed in place during the evaluation of the house.

Three years after starting, construction had reached the stage where a limited performance evaluation could be carried out. Emphasis was on the flow of air through the walls and the effect of it on wall performance and indoor comfort.

6.2 Pressure Across and Flow Through the Walls

At the age of one year, before any of the gypsum wall board had been installed, the 50 Pa air leakage rate was 1.56 ACH. Two years later, after the second storey gypsum board has been fully sealed while the first storey exterior walls were covered, but the joints around windows and along the top and the bottom of the wall were not sealed, the 50 Pa ACH value had decreased to 1.33.

To admit ventilation air to the interior 25 mm diameter holes were drilled through the wall board in the middle of the 400 mm wide stud cavities and some 100 mm above floor level. Fifty-four and twenty-five such holes were drilled into the walls of the second and first storeys respectively. The smaller number of holes for the first storey was to compensate for yet-to-seal air leakage openings of the first storey wall board and the larger pressure difference due to stack action. The 50 Pa air leakage rate was now 1.51, suggesting that the SBPO air barrier was still intact. A direct comparison of the first and third-year values cannot be made in that all of the holes were not drilled into all of the stud cavities while the installation of electrical services and a chimney no doubt increased the equivalent leakage area of the envelope.

To satisfy the ASHRAE Standard 62-81 ventilation requirements, air had to be provided continuously at the rate of 40 L/s and intermittently at 65 L/s. Forty litres per second corresponds to 0.46 ACH. The associated depressurization due to exhaust at 40 and 65 L/S was 9.1 and 12.7 Pa respectively. Air was exhausted by a rheostat-controlled centrifugal fan. Flow rate was

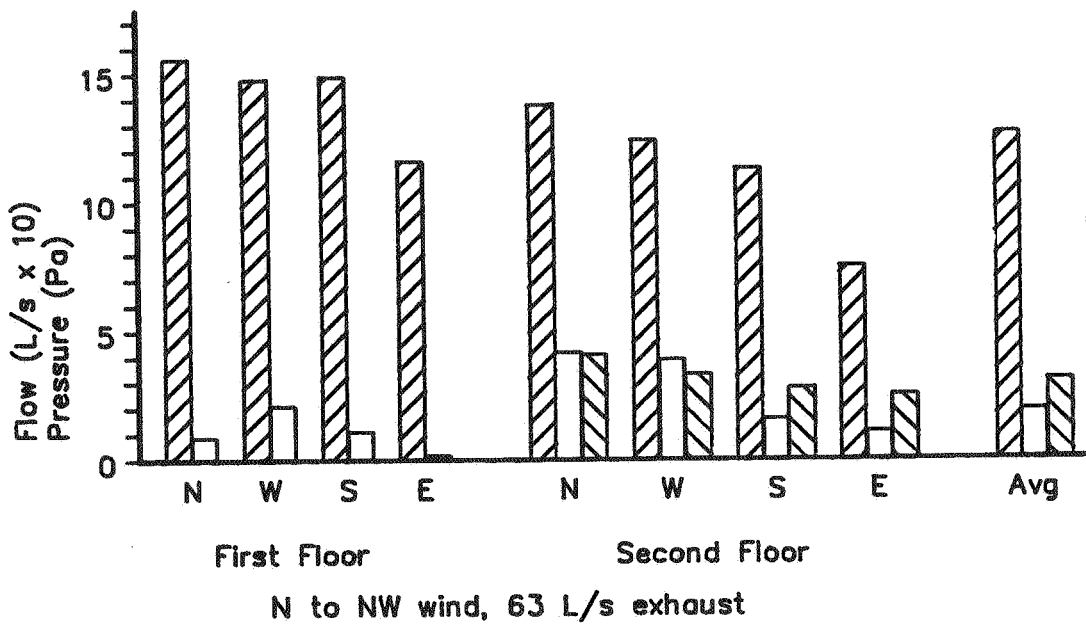
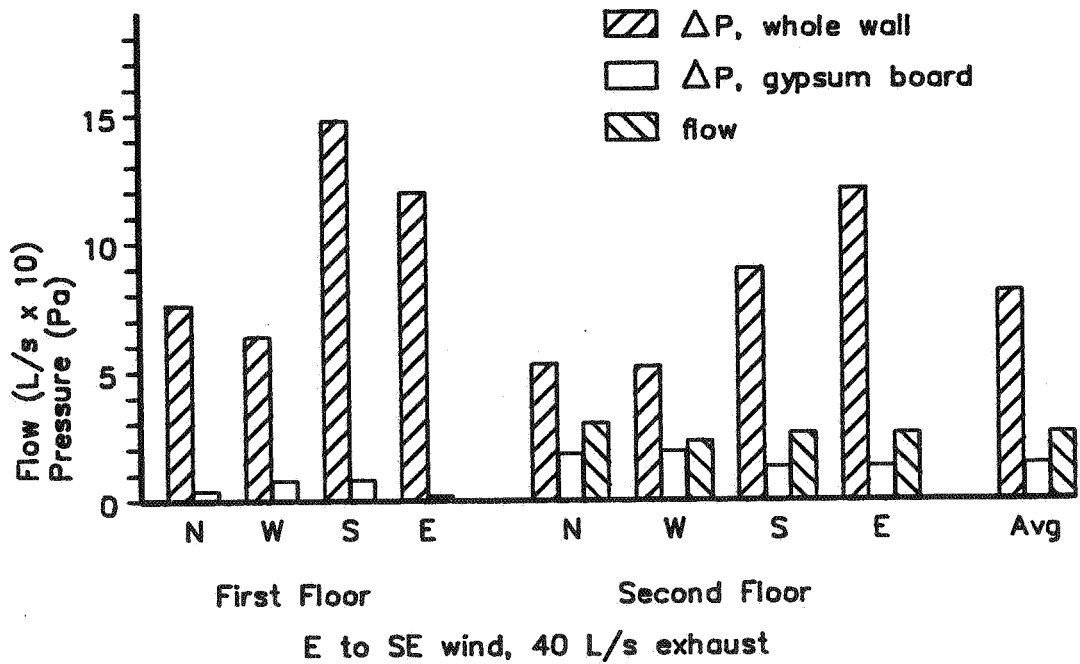


Figure 2. Pressure drop across the entire wall, the gypsum wall board and flow per stud cavity for the four walls with different wind directions and exhaust rates.

determined by measuring the pressure drop in the calibrated air supply duct to the fan by means of a micro-manometer.

Wind speed and direction were continually monitored with a propeller-type anemometer. Pressure drop across the wall and the gypsum wall board was measured with micro manometers. Whenever appropriate, data acquisition systems were used for continual monitoring of parameters. Infiltrating air flow rates through the air inlets were determined manually with the aid of a flow meter employing a hot-wire anemometer for flow sensing.

In Figure 2 pressure across the entire wall and also the wall board as well as flow through the air inlets is presented for exhaust rates of 40 and 64 L/s. The values presented here represent the average of a number of sets, acquired over a period of time when wind varied in direction and ranged in speed from calm to over 30 km/h. Here it is seen that wind direction did affect the pressure distribution. The pressure drop across the wall board was comparatively small, which shows that the SBPO membrane provided the greatest part of the resistance to flow. Variation in flow rates through the four walls were, however, less sensitive to wind speed and direction, suggesting that the individual rooms in this house do receive an adequate share of the ventilation air. The effect of wind on dynamic ventilation air distribution in an urban environment is expected to be even less pronounced due to shelter provided by surrounding buildings. The measured net pressure difference across the walls for the first storey was from 2 to 2.5 Pa higher than for the second storey, which is in close agreement with the calculated difference due to stack action.

6.3 Temperature of the Dynamic Air

In Figures 3 to 5 the temperature of outside air, outside wall surfaces, dynamic air and room air is plotted against time. Figure 3 for the south-facing wall shows that the temperature of dynamic air is close to room temperature. Detailed analysis indicated that at the above ventilation rate the dynamic air was heated to 84 percent of the indoor-outdoor temperature difference. At the higher ventilation rate of 63 L/s, shown in Figures 3 and 4, the degree of tempering has dropped to some 62 percent. The percent tempering is, however, independent of the actual indoor-outdoor temperature difference; dynamic air temperature mimics that of the outside. These observations are in agreement with the model presented earlier and Equation 3.

The effect of solar heating, indicated by the peaks in the south-facing wall surface temperatures and reflected in the temperature of the dynamic air is clearly evident in Figures 4 and 5. Here dynamic insulation could be compared to a diode; it allows solar heat to penetrate the insulation while retarding the flow of heat from the interior. In the meanwhile, there is considerable scope for improvement of dynamic wall design to more efficiently capture solar heat.

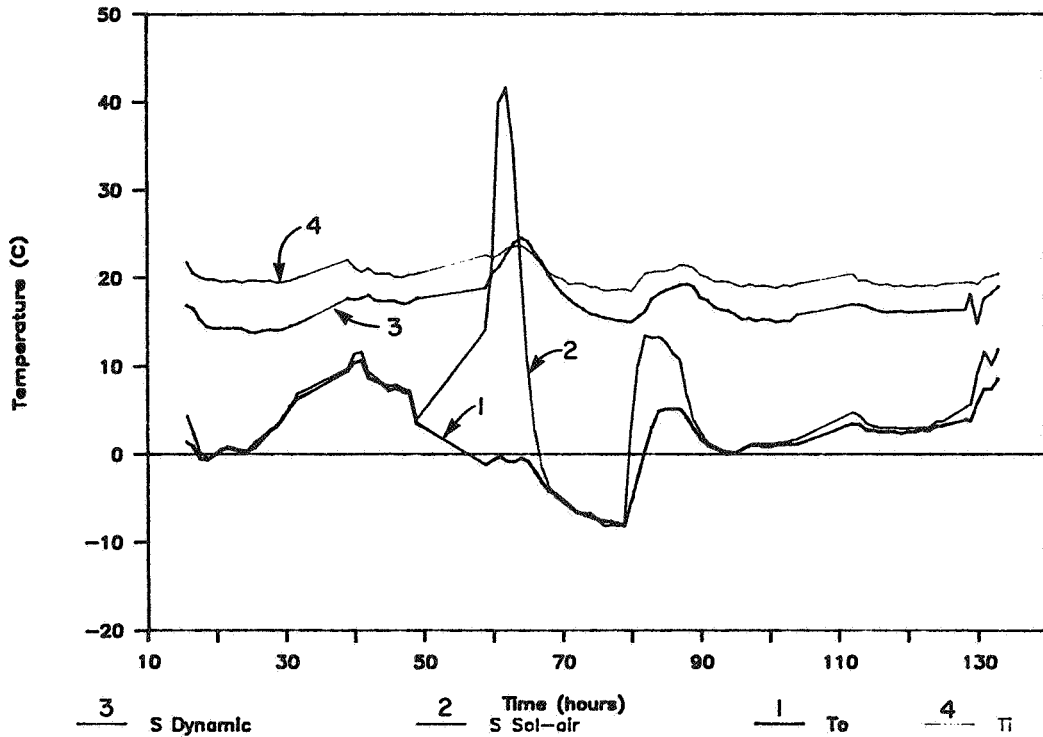


Figure 3. Temperature plot for the south-facing wall for a five-day period while the ventilation rate was 40 L/s. Temperatures are in ascending order: outside air, wall surface, dynamic air and room.

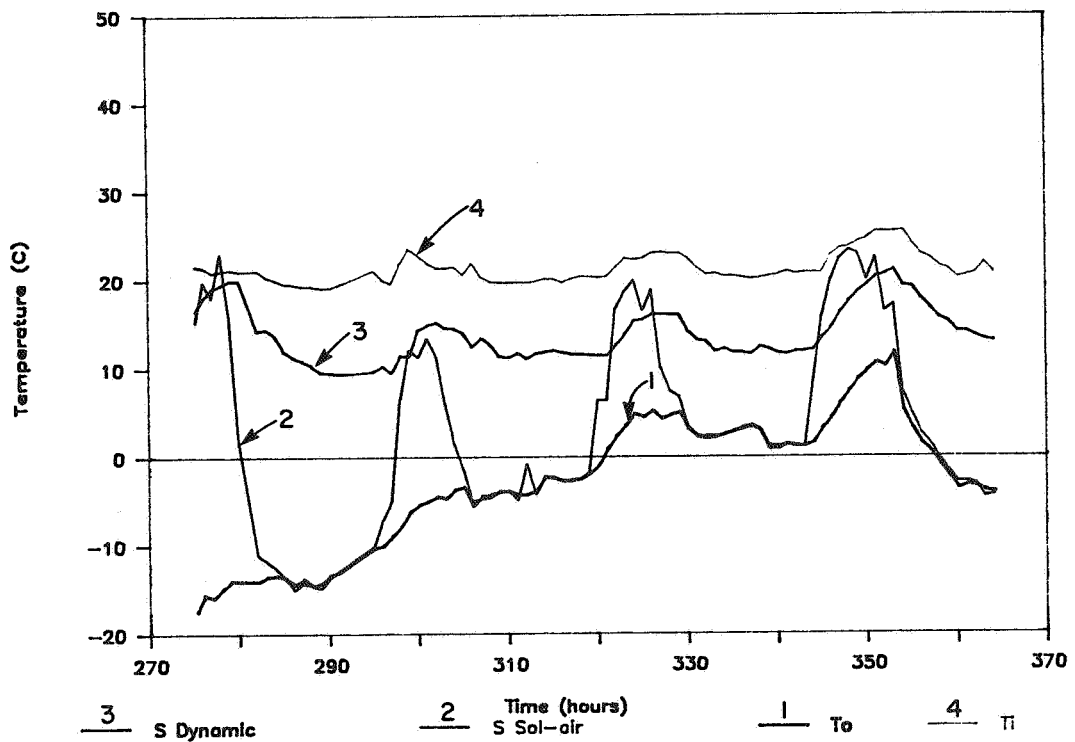


Figure 4. Temperature plot for the south-facing wall while the ventilation rate was 63 L/s.

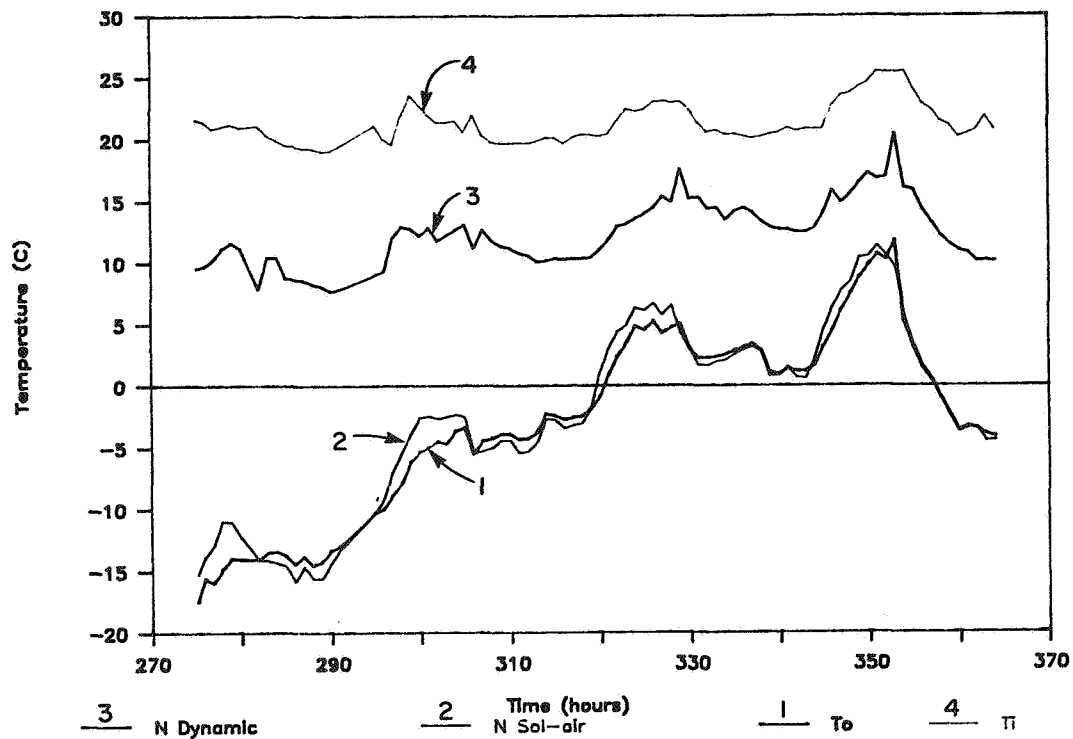


Figure 5. Temperature plot for the north-facing wall while the ventilation rate was 63 L/s.

6.4 Wall Surface Temperatures

One of the early concerns was that air movement through the wall could result in localized cooling of wall surfaces. It was to avoid such cooling by wind that the air barrier was located on the weather-side of the insulation in the first place.

Surface temperature measurements with the aid of thermocouples, an infra-red pyrometer as well as overall monitoring with an infra-red camera did not reveal any temperature anomalies. A closer examination of the air flow through the wall provides a partial answer to the above observation.

At the optimum ventilation rate for this wall, the ventilation air moves through the SBPO membrane at a speed of less than 0.2 mm/s. At this rate the resistance offered by the glass fibres in the insulating sheathing and the stud cavity is too small to channel flow to the inevitable unfilled spaces in the stud cavity. At the mid height of the stud cavity the average velocity is of the order of 3 mm/s. Only in the close proximity of the air supply opening does the velocity increase where the final exit velocity is still less than 0.5 m/s.

The average time it takes ventilation air to complete the passage through the wall is more than 10 minutes, apparently sufficiently long to complete the required transfer of conducted heat to the ventilation air. The air velocities through the bulk of the wall would be too low for the ventilation air to dislodge and carry glass fibres from the insulation. Before a baseboard cover is installed to shield the air supply openings, each air supply opening could be vacuumed to remove loose fibres from the wall.

6.5 Wall Drying

The elimination of exfiltration alone removes one of the major causes for concealed condensation. Controlled infiltration will further lower the relative humidity within the wall cavity to promote the drying of moisture of construction or moisture from other sources. Two conditioned studs, placed in ventilated stud spaces in the north and south walls, lost respectively 6.5 and 5.2 percent of moisture by mass after two months of dynamic operation. How much of this is to be attributed to dynamic action and how much to natural drying in the walls of a heated wood frame house is not clear. At the same time, the vapour pressure of the dynamic air from the north wall was some 320 Pa higher than that of the outside air which shows that moisture was absorbed from the wall by the ventilation air.

Concern has been expressed about a possible health hazard created by mould and mildew formation on the glass fibre insulation and within the wall cavity due to dynamic action. If this is the case, then it should be more of a problem in non-dynamic walls where the drying environment is less favourable. This should, nevertheless, be looked into.

6.6 Operation of Combustion Appliances

The spillage of combustion products and even the outright reversal of chimney drafts is a concern in all houses, and especially so in negative pressure houses. Similarly, radon gas entry with soil air must be controlled.

7. CONCLUSIONS

1. A model has been proposed to explain how dynamic insulation functions at low ventilation air flow rates. It is suggested that at operation at or below the optimum flow rate, wall temperatures remain unchanged while all the heat otherwise conducted through the still-air component of glass fibre insulation in a static wall can be recovered to heat ventilation air.
2. SBPO membrane can be used to form an air barrier on the weather-side face of wall insulation where its installation and inspection are simplified. Moreover, in this location it will also perform the functions of sheathing paper to control rain penetration and wind-cooling of insulation.
3. The SBPO membrane can be used to control air flow through a dynamic wall.
4. In spite of the lack of wind shelter, ventilation air was supplied reasonably uniformly through all the walls in the house described here.
5. Near the optimum ventilation rate the dynamic air was tempered by about 80 percent.
6. No anomalous cooling of wall surfaces was observed during dynamic operation.
7. Drying of wall construction occurred during dynamic action.
8. All indicators point to a substantial energy conservation potential.

Overall, wood frame houses can be modified with very minor changes to become dynamic wall houses. The overall construction cost and materials cost could be reduced on one hand while the quality of the indoor environment could be enhanced on the other. In effect, this can be accomplished by treating the house as a system rather than dealing with each component in isolation. With this approach an attempt was made to build a house where one thing enhances another; a house where the walls and the mechanical systems come together to form a coherent whole.

ACKNOWLEDGEMENTS

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POSTER P1

MEASUREMENT OF SEASONAL AIR FLOW RATES
IN AN UNOCCUPIED SINGLE FAMILY HOUSE

DAVID T. HARRJE¹, DAVID L. BOHAC¹, AND ROY C. FORTMANN²

¹Centre for Energy and Environmental Studies
The Engineering Quadrangle
Princeton University
Princeton
NJ 08544
USA

²GEOMET Technologies, Inc.
20251 Century Blvd.
Germantown
MD 20874
USA

SYNOPSIS

For more than four years air infiltration measurements have been made on two nearly identical side-by-side test houses in Gaithersburg, Maryland, USA. This testing of the complete seasonal weather influence on air infiltration has, in the past two years, included constant concentration tracer gas measurements (CCTG). These multi-zone air infiltration measurements have added further detail on the response of air infiltration into the house to weather changes and the variation of air infiltration between different house locations. Time series data point out the minimal infiltration rates that occur during certain periods. Seasonal data displayed in frequency and three-dimensional plots illustrate the regularity of air infiltration and its relation to delta temperature and windspeed. Regression analysis is then applied to the data sets to reveal the influence of individual parameters such as delta temperature, windspeed and direction. The results show that a simple additive model of delta temperature and windspeed explains most of the air infiltration variations ($r^2 \sim 0.75$) and that more sophisticated models add little to the accuracy of the prediction.

1.0 INTRODUCTION

Our ventilation standards attempt to establish the levels of ventilation air which are required to avoid adverse health effects to human occupants.¹ The amount of air mandated has varied somewhat over the years as our knowledge of the subject has increased. Levels of carbon dioxide, for example, have now been limited to 1000 ppm so as to avoid human discomfort. CO₂ is viewed as a surrogate for other air constituents, including odor.² The more one looks into the question of minimum ventilation for acceptable indoor air quality, the more questions arise. In our larger buildings we ask what is the value of ventilation efficiency, ie., is the outside air entering the building actually reaching the occupants or does one have to supply still more air to make certain every occupant is satisfied? When variable air volume systems are in use, and flow rates drop because the local temperature conditions are satisfied; are the local occupants being supplied at least the minimum amount of "fresh air"?^{1,2} Such questions aimed primarily at mechanical ventilation systems must also be asked of our residential buildings. This paper seeks to add additional information on one aspect of residential ventilation: what are the seasonal air infiltration variations due to weather factors? The site of this investigation is the control house of the pair of nearly identical test houses operated by GEOMET Technologies just outside Washington, D.C.

For more than four years air infiltration information has been gathered on a regular basis for each of the two test houses.³ The measurements were made using the tracer dilution method. The gas chromatographic equipment is situated in a mobile laboratory parked between the test homes. Plastic tubing and an air transfer pump allow air infiltration measurements of the upstairs and downstairs zones of each test house. These locations are shown as X and Y on Fig. 1. The control house has been used for the complimentary, more detailed, air infiltration measurements obtained by the constant concentration tracer gas (CCTG) equipment.

As indicated in Fig. 1, CCTG infiltration measurements were conducted in five separate upstairs zones and a single downstairs zone. This figure also indicates the locations of the sample and injection points along with the positions of the small mixing fans that were used during the CCTG measurements. Under many circumstances natural room air circulation patterns can prove sufficient to mix the room air, thereby allowing one to eliminate the small air mixing fans used in this study. Studies in this house showed that even without the fans the deviation in the concentration increased only slightly.

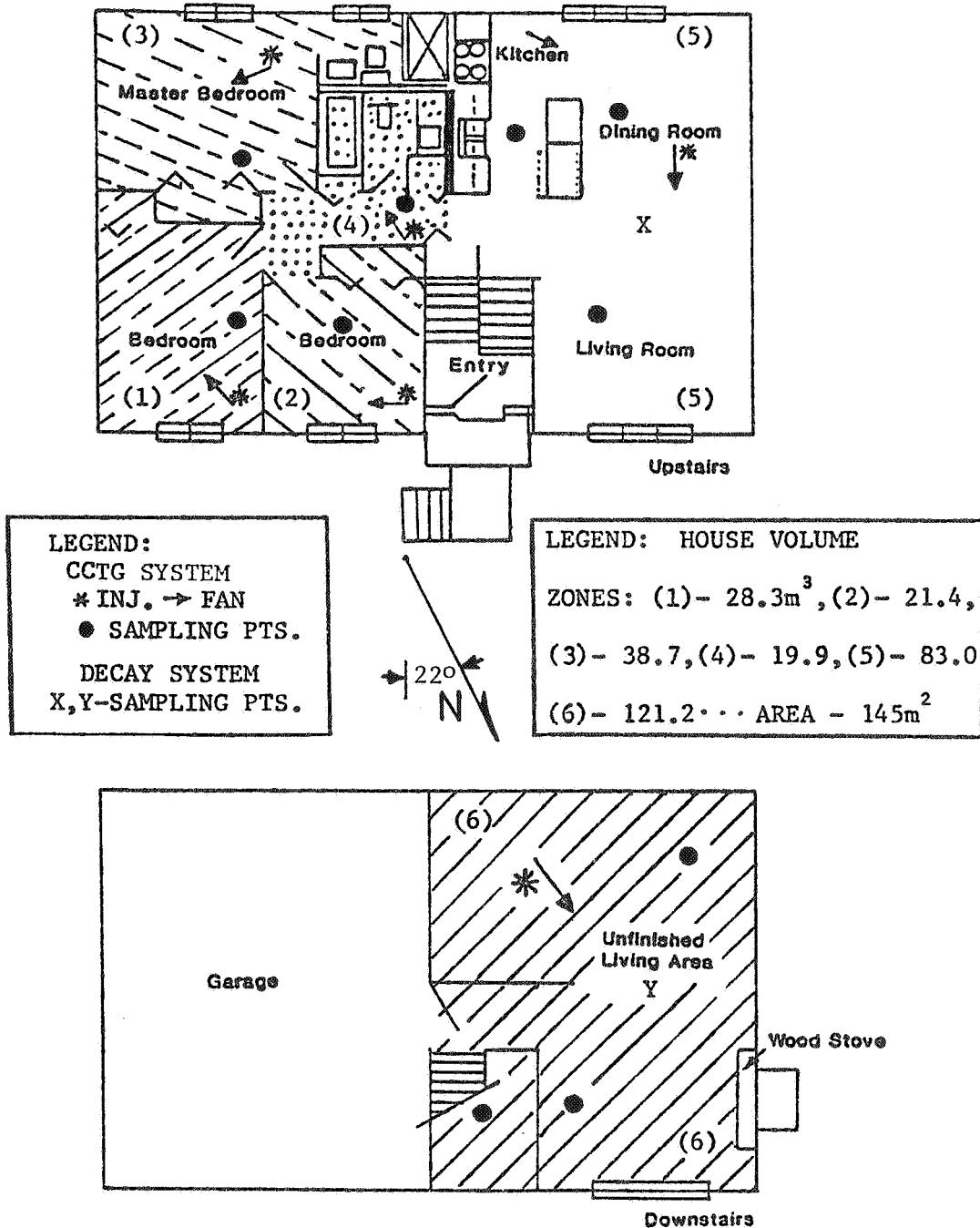


Fig. 1. Floor plans, sampling points & fans, and volumes & floor areas of control house. Six zones evaluated for air infiltration by the constant concentration method are numbered.

The constant concentration system and control algorithm used in this study has been described in detail in previous AIVC conference proceedings.^{4,5} The method consists of injecting the proper amount a dilute mixture of the tracer gas (SF₆ at typically 0.15% concentration in air) into each zone so that the concentration is kept constant at the target in all the zones. By keeping the concentration constant, the air infiltration rate into each zone is simply equal to the tracer injection rate for the zone divided by the target concentration. While the CCTG system normally measures infiltration rates, intermittent measurements of certain interzone rates are possible by discontinuing injection in selected zones. These types of measurements are not included here but are discussed in another paper presented at this conference.⁶

In order to keep the concentration at the target level the system measures the tracer gas concentration, calculates the rate of injection needed for each zone, and injects the tracer gas at a variable rate - all on a time scale that allows adequate control of the tracer concentration. The system consists of an electron capture gas chromatograph, a series of ten sample and injection lines, valve control electronics, and a microcomputer-based data acquisition system. The concentration measurement takes approximately 30 seconds to complete. Injection begins at the start of the cycle and can continue until the last half second of the cycle.

It is important to note that, instead of performing only a single injection in a zone between samples of the zone, the system performs an injection into every zone during each 60 second cycle. This method more closely approximates constant injection. At the end of each hour of operation the average concentration, rms deviation in the concentration from the target, and the estimated average infiltration rate are stored to a disk file. Recent modifications to the system allow the user to interactively graph this data on the screen or access the data via modem communications from a remote location while continuing the normal operation of the system. In addition, the system records hourly measures of the concentration of a reference tank to adjust for the drift of the gas chromatograph. Also, the most recent version of the CCTG system utilizes an improved version of the gas chromatograph with molecular sieve columns and backflushing which provides reduced measurement and cycle times of 10 and 30 seconds.

Weather data, which are an important part of the information set, are supplied from the between-house mobile laboratory and includes: outside temperature, wind speed, and wind direction.

The infiltration measurements were conducted during three separate periods of time: in the spring from March 21 to April 2 of 1985, in the summer/fall from August 20 to September 9 of 1986, and in the winter from January 14 to 22 of 1987. The final data set includes 120 observations from the spring, 301 from the summer/fall, and 137 from the winter period.

2.0 TIME SERIES DATA

As was previously described in Ref. 4, the individual rooms and zones in the control house experience a wide variety of air infiltration rates. Typical of such recently collected data is the plot in Fig. 2

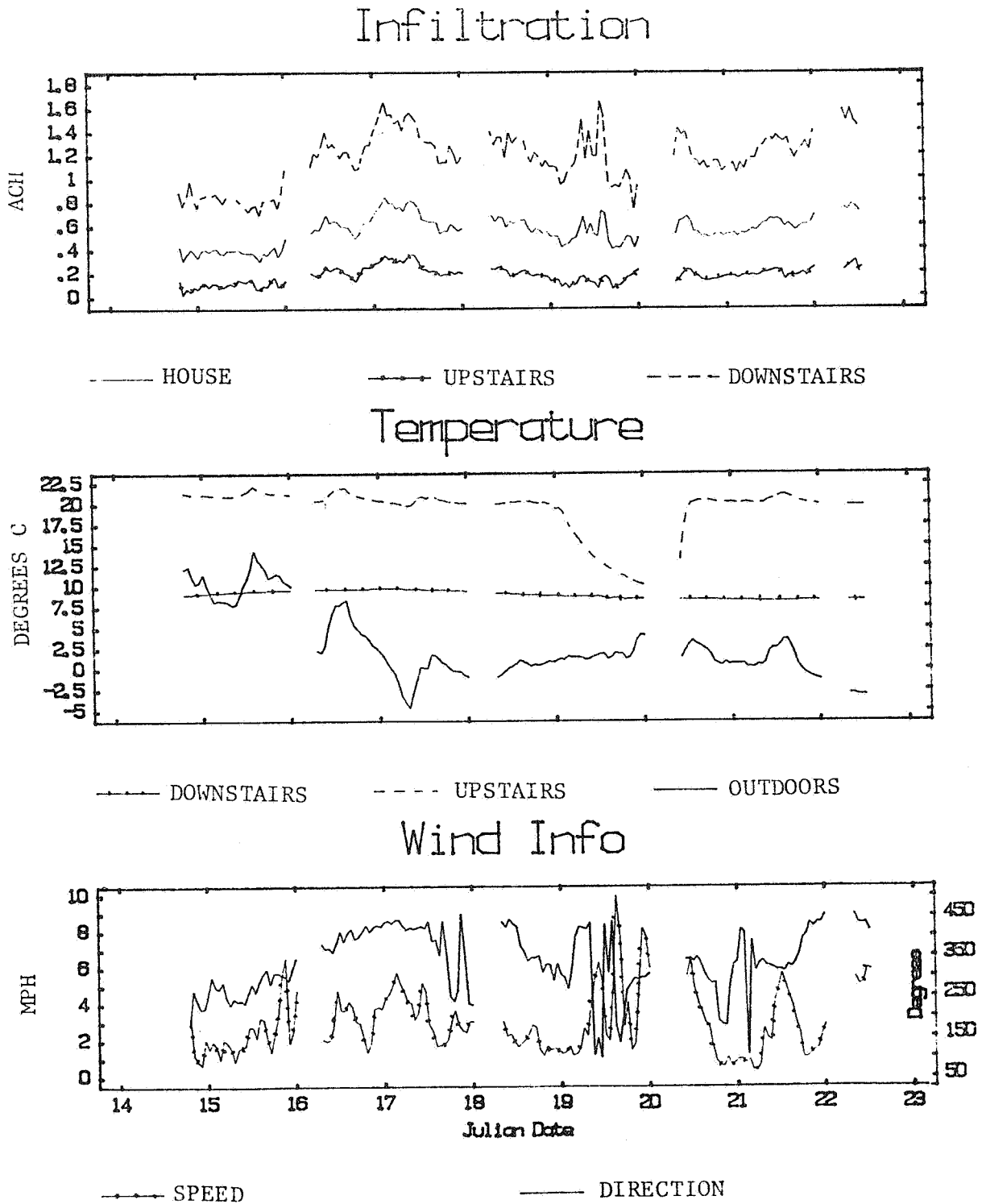


Fig. 2. Time series air infiltration data from the winter data set. Five upstairs zones plotted as "upstairs" in this figure.

which displays the winter data of the whole house, downstairs, and upstairs air infiltration over time, as well as the downstairs, upstairs, and outdoor temperatures, together with wind speed and direction. The upstairs infiltration rate is an aggregate of the five upstairs zones. The air infiltration variation points out the source of concern as to whether or not ventilation rates are consistently sufficient to satisfy indoor air quality requirements in all areas of the house. Although the basement levels for air infiltration frequently exceed 1 ach, the upstairs levels (and those for the individual upstairs zones) often fall below 0.1 air change per hour (ach) and thus internal air circulation may be required to meet ventilation standards.

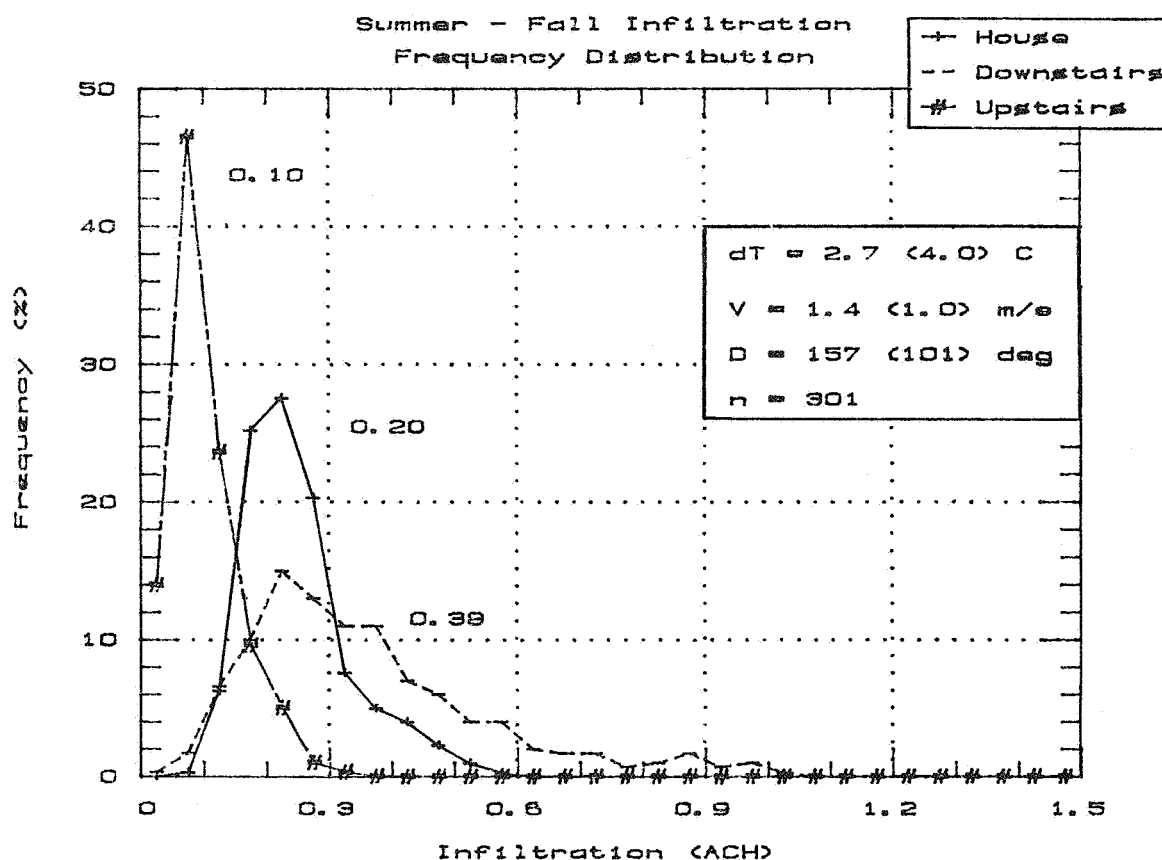


Fig. 3a. Typical frequency distribution plot based upon summer-fall data set. Three plots are for total house, upstairs and downstairs.

3.0 SEASONAL AIR INFILTRATION VARIATIONS

3.1 Frequency Plots

It is also useful to plot the seasonal air infiltration data for the upstairs, downstairs, and whole house based on frequency of occurrence. These relatively short-term test results, as shown in Figures 3a, 3b, and 3c illustrate the same characteristic profiles as described in Ref. 3 (also shown in Ref. 2) for longer term tracer gas decay studies. Each of the frequency plots provides information on the average and standard deviation of the delta temperature, wind

velocity, wind direction, and number of data points. The infiltration frequency and weather data allow examination of the percentage of time ventilation standards are met and under what weather conditions they are met.

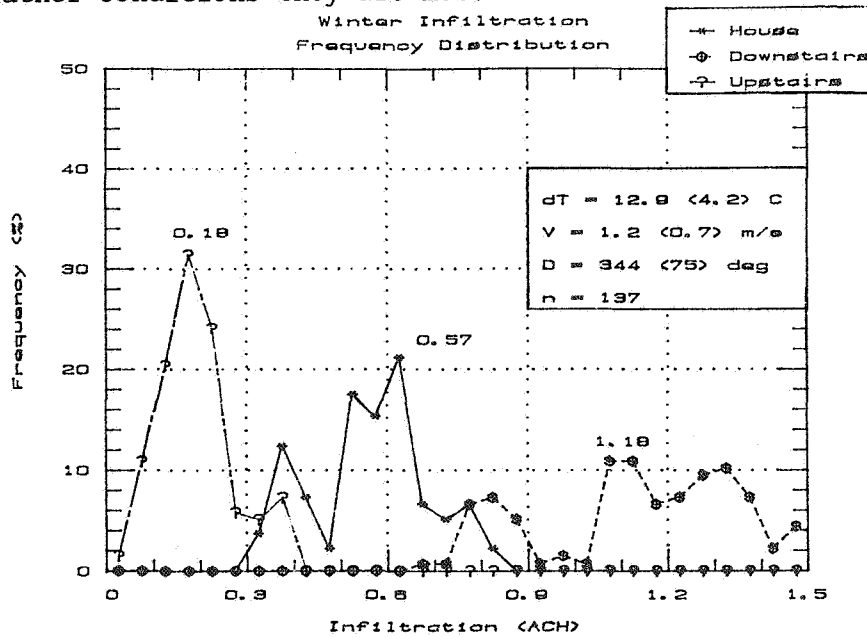


Fig. 3b. Typical frequency distribution plot for winter data set.

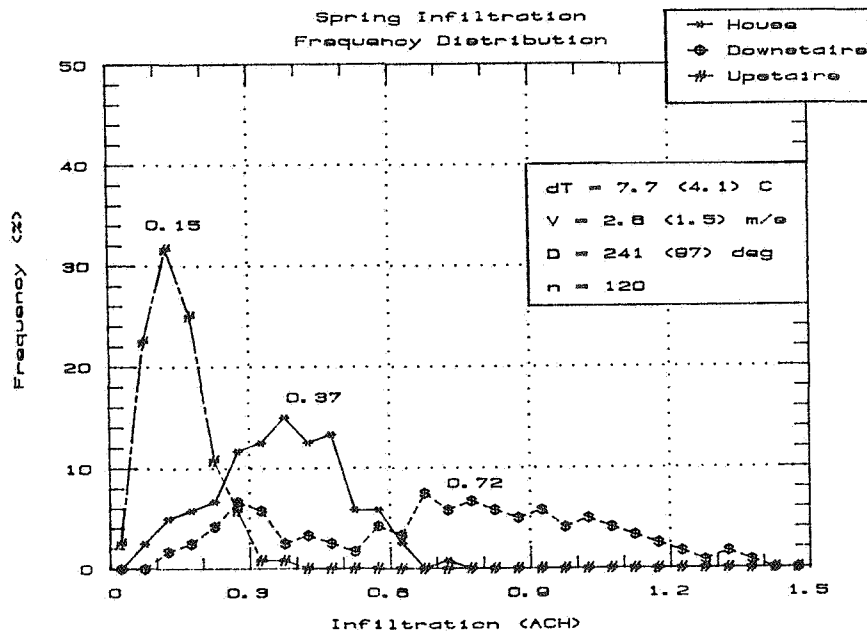


Fig. 3c. Typical frequency distribution plot for spring data set.

For this house ASHRAE standard 62¹ specifies a minimum ventilation of 0.44 ach for the whole house and 0.53 ach for just the upstairs rooms. The proposed standard revision, 1987, specifies a minimum of 0.35 ach for the house and individual rooms. For the summer - fall period (Fig. 3a) only 1 hour of the 301 hours whole house measurements equals or exceeds 0.5 ach and only 20% exceeds 0.25 ach. The winter data presents a much improved air exchange rate, where 75% of the time 0.5 ach is exceeded and there are no periods less than 0.25 ach. Finally, the spring data indicates 15% above 0.5 ach and 20% less than 0.25 ach. These results indicate that the closed house infiltration rates do not meet minimum standards over all the seasons.

The frequency plots show that the minimum ventilation standard of 0.53 ach for the upstairs is never met for any of the recorded data. The 1987 proposed standard of 0.35 ach is met less than 1% of the time in the spring and winter and not at all in the summer - fall. However, during the winter the air flow from the higher ventilated downstairs may provide adequate ventilation air depending on the degree of mixing between the two areas. During the two other periods the ventilation air from the downstairs would seldom be sufficient.

3.2 3-Dimensional Displays

One method we have found to be useful in interpreting the air infiltration data for the test house during the various seasons is a three-dimensional display. Figures 4, 5 and 6 indicate displays for spring, summer/fall, and winter data. Looking at the temperature

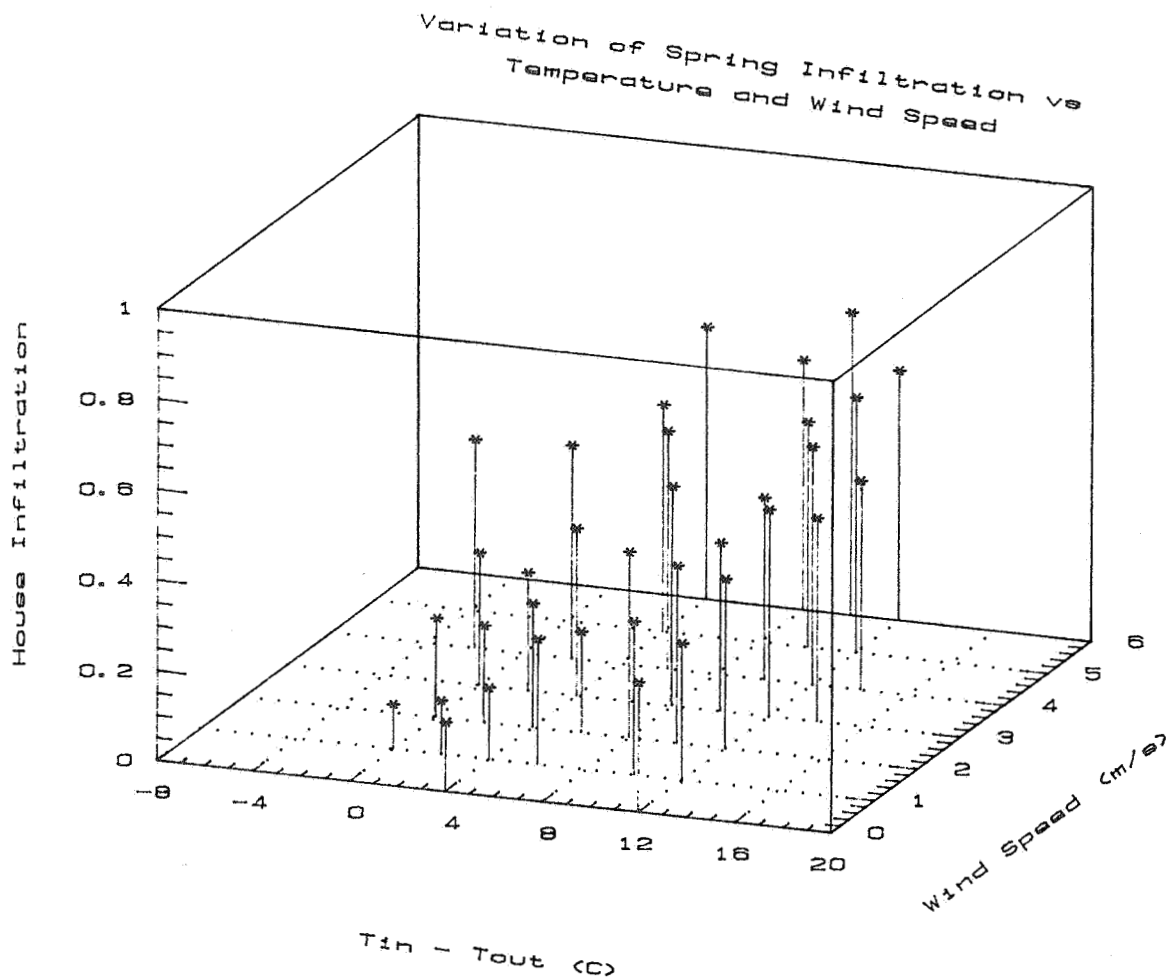


Fig. 4. Three-dimensional data display for the spring data set.

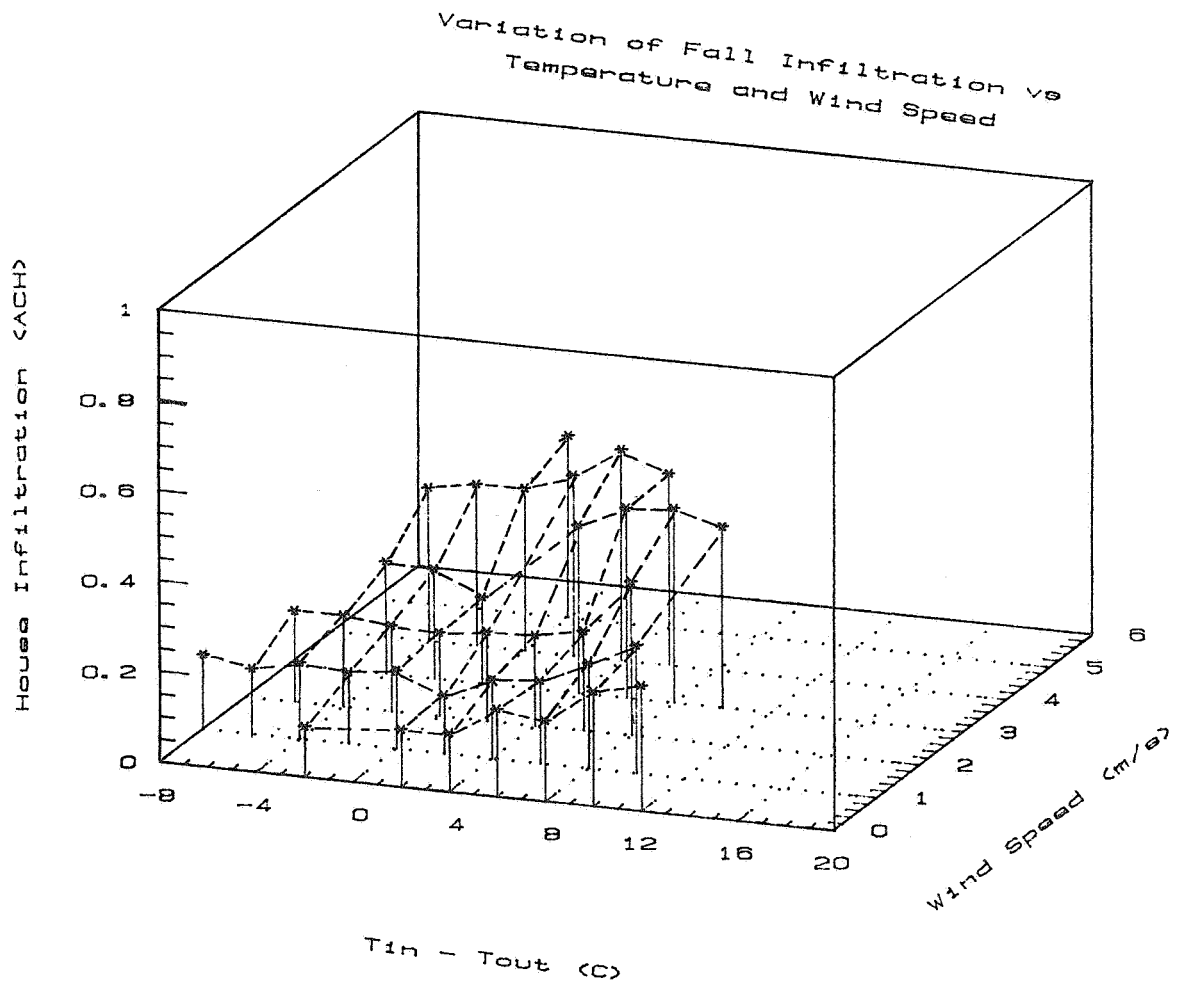


Fig. 5. Three-dimensional data display for the fall (late summer) data set.

windspeed matrix, the fall data are seen to cover a similar windspeed range (0-4 m/s) when compared to the winter data but, as expected, a different delta temperature range (-8 to $+12^{\circ}C$ versus 2 to $20^{\circ}C$). The spring data occupies an intermediate range of delta temperature (0 to $12^{\circ}C$) covering the overlap of the fall and winter delta temperature data, but in addition extends over a wider range of windspeeds, to 6 m/s. Contours for constant windspeed and for constant temperature difference are illustrated in the fall air infiltration data, in Fig. 5. Unfortunately, the extremes of temperature and wind conditions for the various seasons in the Washington, D.C. area did not take place during the intervals when the CCTG equipment was in place. The extremes in delta temperature can reach $35^{\circ}C$ in winter, and $-15^{\circ}C$ in summer in that area, and winds to 10 m/s are not unusual.

For the 3-D display to be useful one must group the data in bins sufficiently coarse so that one can recognize the nature of the "data forest" and not have general trends obscured by the individual "data trees." The figures 4, 5, and 6 use bin widths of 1 m/s for windspeed and $2^{\circ}C$ for delta temperature. These figures show the

expected positive relationship between delta temperature and windspeed to house infiltration. However, a quantitative analysis is required to better evaluate the relationship between these variables.

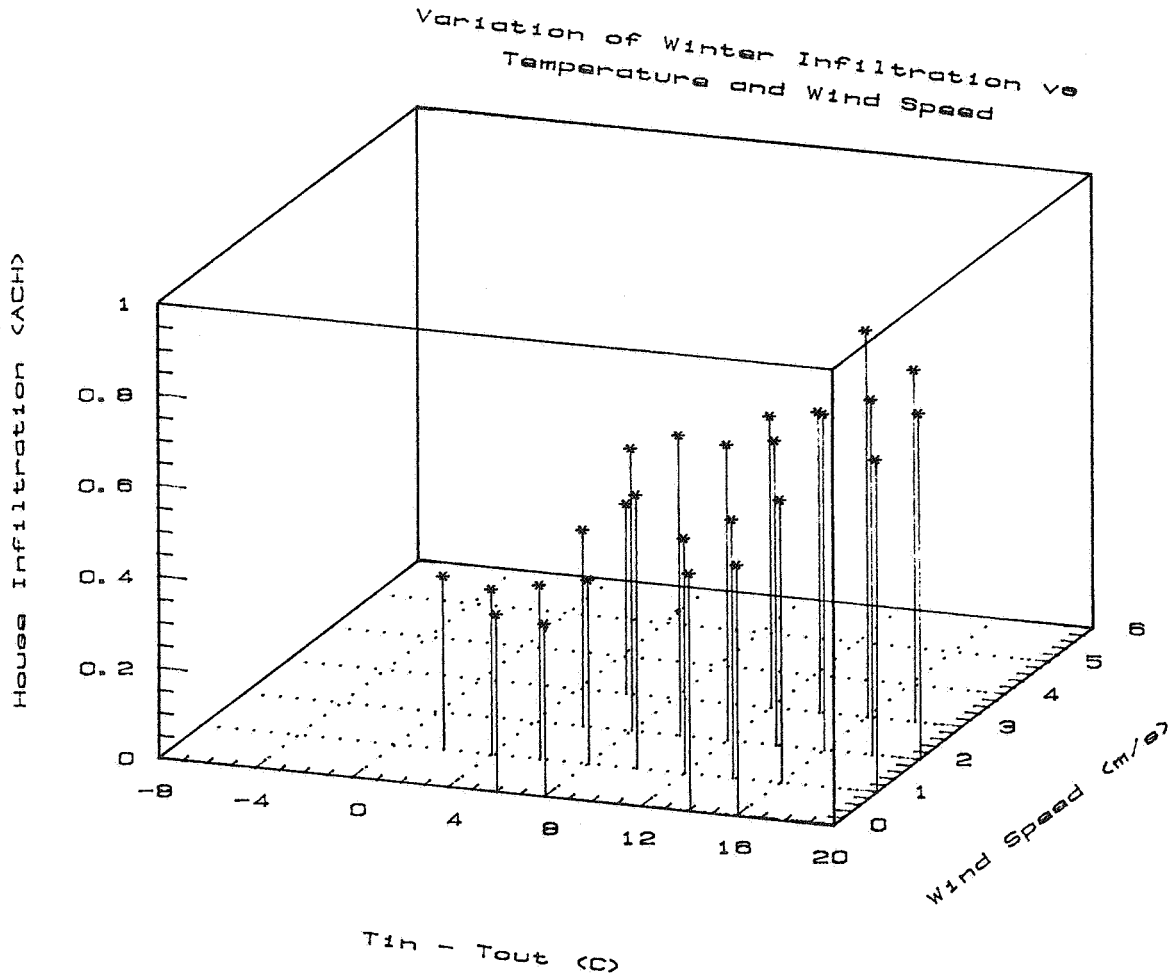


Fig. 6. Three-dimensional data display for the winter data set.

4.0 REGRESSION ANALYSES

Traditionally the model of air infiltration (AI) for an individual house has often taken the form of a regression relationship:⁷

$$AI = A + B \cdot \Delta T + C \cdot V$$

where a constant value A adds to a linear relationship of delta temperature and a third term relating wind speed. Variations have added an exponent to the windspeed term or sometimes wind directional information has been added.^{8,9}

The origins of the model variations are that the air flow through adventitious openings in the envelope of the building can generally be approximated by the equation: $Q = K \cdot (\Delta P)^n$, where K is the flow coefficient, n the flow exponent and ΔP the pressure difference across the opening.¹⁰ The pressure difference from wind impinging on a surface is proportional to V^2 , and is influenced by the impingement angle. The pressure difference from stack action is related to:

$$P_s = \rho_o g 273 h \left[\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right]$$

which is proportional to $\Delta T/T_{ext}$ (K), where ρ_o is the air density at 273K and ambient pressure, h is the vertical distance between openings, and T_{ext} and T_{int} refer to the exterior and interior temperatures.¹¹ If it is assumed that the total building pressure from both the wind velocity and stack effects is equal to the sum of the pressures from the two effects acting alone, then the flow rate from both effects is given by:¹²

$$[a\Delta T^{1/n} + bV^{1/n}]^n$$

The regression results for the three seasonal data sets and the three data sets combined are summarized in Tables 1 and 2. The regression

Table 1

RESULTS OF REGRESSION ANALYSIS FOR VARIOUS MODELS

	<u>Model</u>	<u>r² Value</u>			
		Fall/ Summer	Winter	Spring	Total
(1)	P1 + P2 ΔT	0.113	0.623	0.293	0.666
(2)	P1 + P2V	0.377	0.317	0.656	0.135
(3)	P1 + P2 ΔT + P3V	0.710	0.852	0.780	0.790
(4)	P1 + P2 ΔT^m + P3V ^k	0.725	0.859	0.790	0.813
(5)	P1 + P2 ΔT + P3V + P4V cos($\theta - \theta_o$)	0.740	0.875	0.829	0.817
(6)	P1 + [(P2 ΔT) ^{α} + (P3V) ^{α}] ^{1/α}	0.718	0.858	0.789	0.800

approach begins with simple constant and single variable models with ΔT and windspeed (V) and gradually increases the model complexity. The third model is a linear additive relation with ΔT and V. The fourth model uses variable exponents of m and k for the ΔT and V terms and is used to examine the preferred exponents of the stack and wind terms. The fifth is the linear model with a windspeed direction term (|cos($\theta - \theta_o$)|) added and studies the effect of wind direction. The absolute value of the cosine of the wind direction minus a

reference direction was used because the house is sheltered by houses on both sides and is relatively open on the front and back sides. Finally, the sixth is a complex addition of terms, $P1 + [(P2\Delta T)^\alpha + (P3V)^\alpha]^{1/\alpha}$ and is equivalent to the above flow equation for wind and stack effects. It examines the preferred value of n (here, $\alpha = 1/n$).

Table 1 summarizes the results of the correlation coefficient for the three seasonal data sets as well as the combined data set for the six models. The results from the first two models show the effect of the weather pattern during the periods. For the winter period, when the stack effect dominates, much of the variation in the data ($r^2 = 0.623$) can be explained with only the ΔT term. During the spring the wind has a greater effect on the infiltration level and the data is better explained with the windspeed term. Using the additive model of the two terms yields values of r^2 from 0.71 to 0.85. This range of correlation is similar, although slightly lower, to those reported by Nagda et al in Ref. 3. A scatter plot of the predicted versus measured house infiltration rates for the combined data set is displayed in Fig. 7. This plot shows the agreement between the predicted and measured infiltration rates ($r^2 = 0.79$) for the 480 observations.

Table 2

Estimated Parameters From Regression Analysis
(see models Table 1)

<u>Data Set</u>	<u>m</u>	<u>k</u>	<u>θ_o</u>	<u>α</u>
Summer/Fall	1.23 (0.17)	1.42 (0.16)	14.8 (6.0)	1.35 (0.16)
Winter	0.65 (0.23)	0.71 (0.22)	31.1 (4.6)	0.57 (0.20)
Spring	0.49 (0.27)	0.89 (0.19)	38.7 (3.3)	1.85 (0.38)
Total	1.45 (0.09)	0.45 (0.14)	32.6 (2.9)	1.77 (0.19)

Table 2 displays the estimated parameters (m , k , θ_o , and α) obtained from the regression analysis of models 4 - 6. The results for m and k range from 0.45 to 1.45 and show little consistency. Along with the small increase in r^2 from the linear additive model (3), this indicates that coefficients of 1.0 for the two terms are as reasonable as any others. The value of θ_o obtained from the wind direction term in model 5 is relatively constant - varying from 15 to 39°. Since the house faces 22° East of North, this result is consistent with the greater degree of sheltering that exists on the sides of the house. However, the addition of the wind direction term typically increased the r^2 by only 0.03 (see Table 1) from model 3, indicating a weak dependence of the house infiltration to wind direction. The results from the sixth model show one estimate of the exponent α below 1.0 (0.57 for the stack dominated winter period) with the rest above 1.0. α for the combined data set was estimated to be 1.77 or $n = 0.57$. Given the wide variation in the estimates of α and the very small improvements in the r^2 from the additive model (3), no conclusive value of α can be determined. It appears that the linear model ($\alpha = 1$) performs as well as a square root of the sum of the squares ($\alpha = 2$) model.

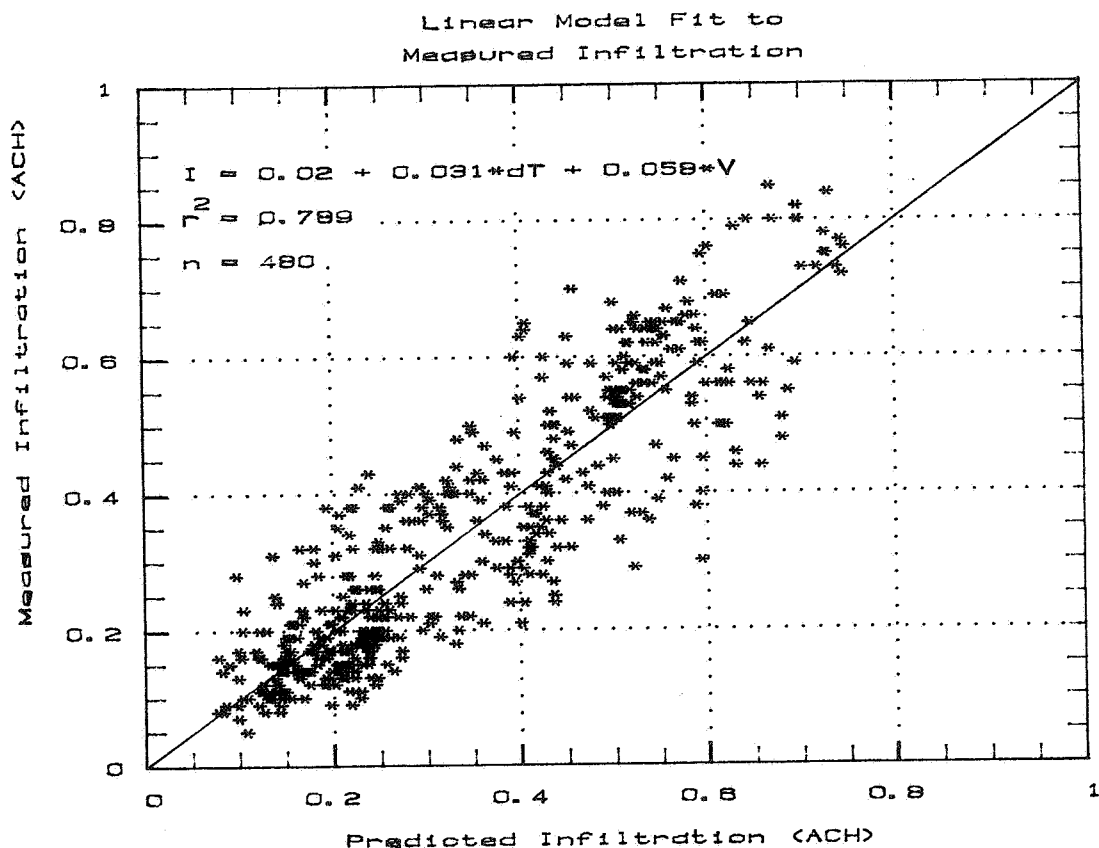


Fig. 7. Scatter plot of the total data set illustrating the agreement between predicted and measured air infiltration rates.

Since the CCTG system provides infiltration measurements for not only the whole house but also individual zones, the analysis of the relationship of weather parameters to infiltration can also be performed for the individual zones. It is expected that the individual zones will respond differently than the whole house to certain factors such as the windspeed and direction. For example, while the wind direction has been shown to have a small effect on the house infiltration because of the local sheltering, it should have a more significant effect on the individual zones since the outside walls of a zone typically face only one or two directions.

To study this hypothesis, regression analyses are performed for the downstairs zone for the fall period. The linear additive model (3) applied to this data set results in a r^2 of 0.737. The wind direction effect is examined by adding a term ($\cos(\theta - \theta_0)$) to the model. This term differs from that used in model (4) above since the cosine of the direction and not the absolute value of the cosine is used. This form is used because the zone should be sheltered by the rest of the house on one side and exposed to the outside on the other. The results of the regression analysis with the direction term show an increase in the r^2 to 0.830. Thus, the direction term is able to explain 35% of the deviation of the data about the model that was not explained by the linear model. The value of θ_0 is estimated to be $34^\circ \pm 5^\circ$. This direction corresponds to a wind

impinging nearly perpendicular to the front of the house. This is a reasonable value since the only windows downstairs are located on the front wall, the side walls are sheltered by a house to one side and the attached garage on the other, the back wall is sheltered somewhat by the rear deck, and the effect of the wind on the front wall could be increased by the front landscaping that is sloping up to the house. A scatter plot of the predicted versus measured downstairs infiltration rates the the fall period is displayed in Fig. 8. This plot shows the agreement between the predicted and measured infiltration rates ($r^2 = 0.83$) for the 229 observations.

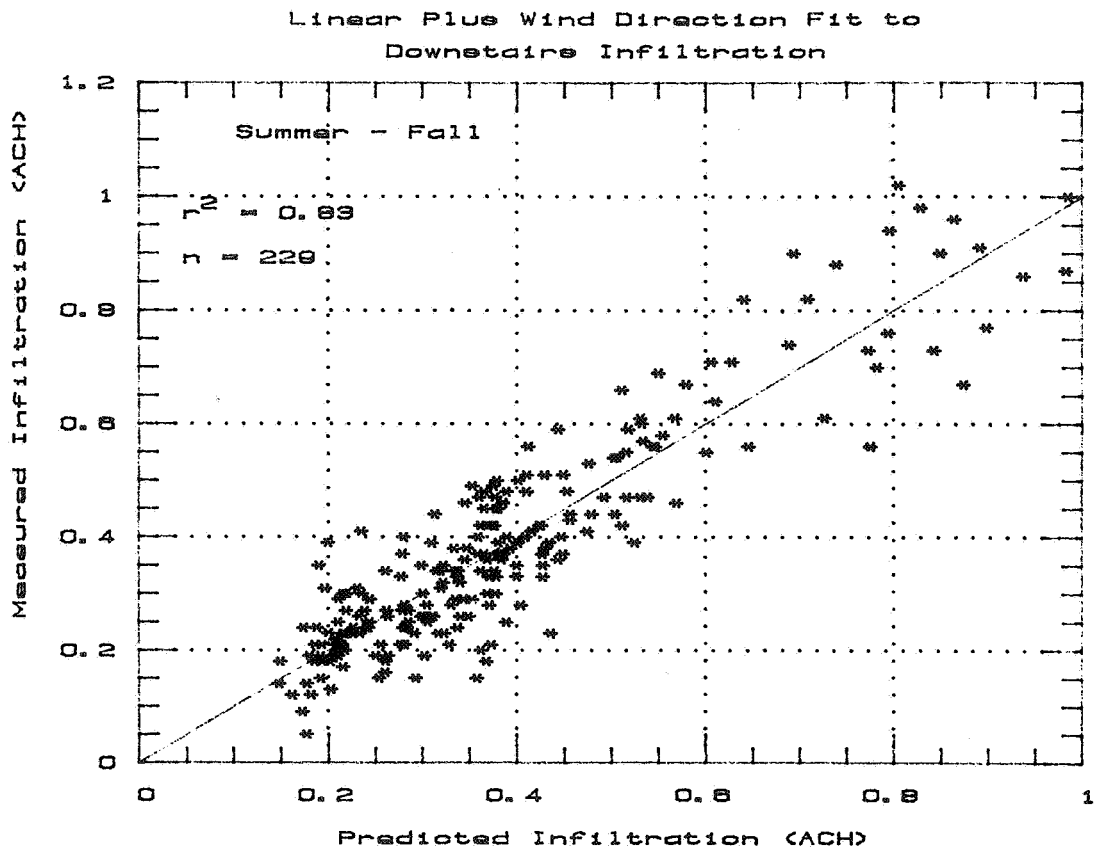


Fig. 8. Scatter plot of the measured air infiltration versus the predicted air infiltration using downstairs data and the linear model with wind direction.

5. CONCLUSIONS

This paper has presented a number of ways of viewing seasonal air infiltration data as collected by constant concentration tracer gas methods. The data clearly point out the variability of ventilation provided by air infiltration due to both weather and house location. The data show that the infiltration in the upstairs never reached the minimum level recommended by standard 62 and that the whole house infiltration often did not reach the minimum. To fulfill ventilation requirements use of window openings or mechanical ventilation would appear to be necessary to supplement or substitute for the inadequate air infiltration during certain

portions of the year. From a modelling standpoint, the ability to look at details of where the air infiltration is taking place in the house, as well as the seasonal weather information, adds to the capabilities of generating an appropriate physical model for the air infiltration events. The regression analysis indicates that the infiltration is accurately predicted with a additive model of delta temperature and windspeed. More complex models which included the effect of wind direction and more sophisticated combinations of the parameters added little to the predictive capability of the model.

6. ACKNOWLEDGEMENTS

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VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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POSTER P2

A PORTABLE UNIT FOR MEASURING VENTILATION EFFICIENCY

N.O. BREUM AND J. SKOTTE

Danish National Institute of Occupational Health
Department of Industrial Hygiene
Baunegaardsvej 73
DK 2900 Hellerup
Denmark

SYNOPSIS

A computerized portable unit for measuring the ventilation efficiency by the tracer gas technique is described. The hardware of the unit is designed from readily available equipment. The software of the unit is menu-driven to be operated by computer non-experts. The software include several analytical models of ventilation processes and in the present study is discussed age analysis and the air exchange efficiency. In a field study the ventilation process of a non-occupied lecture hall was characterized by the portable unit, and in case of almost isothermal conditions the measured air exchange efficiency was 54% indicating a complete mixing. It is emphasized that the portable unit may also be used for characterizing the indoor air pollution.

SYMBOL LIST

		<u>Units</u>
A	mean age of air	h
C	generic symbol for concentration	ppm
$C(\infty)$	equilibrium concentration	ppm
$C(0)$	concentration at $\tau=0$	ppm
$C(\tau)$	concentration at time τ	ppm
MO	zeroth moment from origin of the concentration vs time	ppm h
M1	first moment from origin of the concentration vs time	ppm h ²

m	amount of tracer gas released as a pulse	m^3
NO	zeroth moment from origin of the complementary normalized concentration vs time	h
N1	first moment from origin of the complementary normalized concentration vs time	h^2
q	flow rate of tracer gas	m^3/s
Q	flow rate of air	m^3/s
V	volume of a room	m^3

Greek symbols

τ	time	h
τ_n	time constant of a ventilation system	h
τ_p	the "local time constant" of a point p	h
τ_o	given time interval	h
ϵ_a	air exchange efficiency	
β	off-set	

Subscribts and other symbols

e	refers to the exhaust air
p	refers to an arbitrary point p
< >	refers to the room average

1. INTRODUCTION

A common technique for ensuring an acceptable indoor air quality and thermal environment is mechanical ventilation. A number of ventilation system designs are in common use, and qualitatively the pattern of airflow can vary from one extreme (short circuiting) to the other extreme (displacement flow). Between these extremes is perfect mixing¹.

A proper air distribution in a room is essential, and the concept of age distribution is useful in the quantification of mixing and flow in a confined space. For this purpose the experimental impulse-response tracer gas technique is well established², and by the present study is reported details of a portable computerized unit³ using this technique for measuring and modelling the ventilation process in a room. Some of the analytical models included in the software of the portable unit are the age distribution of the air in a room, the ventilation efficiency, the air exchange efficiency, the air change rate, and airflows of a two compartment model. In the present study, however, is included only details of modelling and estimating the age distribution of air and the air exchange efficiency. The unit is designed to allow an easy characterization of the ventilation process in a room, which finally is illustrated by an example.

2. THE PORTABLE MEASURING UNIT

For the purpose of documenting a ventilation process by the tracer gas approach a detailed experimental procedure is required, including a proper strategy for injecting the tracer

gas, adequate hardware for measuring the tracer gas concentration vs time, and finally an analytical model for the interpretation of the data obtained. As previously reported² common strategies for the injection of the tracer gas are constant release (step-up), decay (step-down) and the pulse injection mode. In the present study the equipment for the injection of the tracer (SF_6) is a release directly from a compressed gas cylinder and controlled by a needle valve and a calibrated rotameter to an accuracy³ of $\pm 3\%$.

The hardware of the highly automated unit (fig. 1) is designed from readily available equipment⁴. By gas tight pumps air from up to 8 sample lines (25m length, 10mm i.d. tygon tubing) are continuously sucked through the sample lines and the manifold of 3-way solenoid valves, and air from each line is sequentially delivered to the gas analyzer at a flow of 33 l/min. The present gas analyzer is an IR-analyzer (MIRAN 80, Foxboro Analytical) with a time constant of 9.6 sec at a 33 l/min sampling rate. During an experiment the sequence of operations and the data acquisition is run by a portable IBM-compatible computer (COMPAQ 286). Continuously upgraded test results are displayed on location.

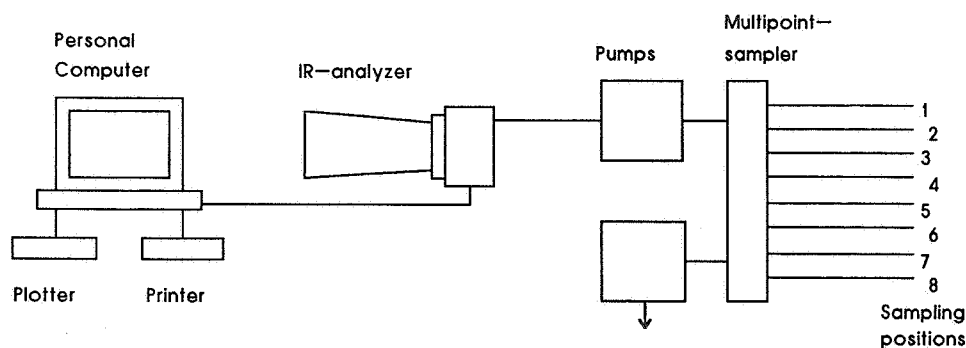


Fig. 1. The multipoint tracer measurement equipment.

The software running the outlined hardware is designed to be menu-driven and to be operated by computer non-experts. The two main menus of the software are entitled setting up the system and modelling, respectively. Some major points in setting up the system include preselecting of

- the tracer gas to be used: the software may contain the calibration curves of up to 9 different gases. In the present study SF₆ is used, the calibration ranging 0.2-50 ppm with an accuracy³ of +/-2.5%.
- the gas analyzer to be used: a digital or an analog output is accepted, and one sample line may, if needed, contain a span gas for an automatic correction of a possible drift in the baseline of the analyzer.
- the measurement cycle: usually a 45 sec step period of the sequential sample line scanning is used ensuring a 1% maximum bias in data due to an insufficient purging of the present gas analyzer.
- the number of sample lines to be used: each line may be described by a 40 character free text.

When the system has been set up measurements are running until a manual stopping procedure is applied. All data obtained are stored on a disk for the subsequent modelling.

3. THE ANALYTICAL MODEL

The modelling software menu include several analytical models, but in the present study is only discussed the mean age of air and the air exchange efficiency. By definition⁶ the air exchange efficiency $\langle \epsilon_a \rangle$ is computed by the equation

$$\langle \epsilon_a \rangle = \tau_n / 2 \langle A \rangle \quad (1)$$

where τ_n is the nominal time constant of the ventilation system and $\langle A \rangle$ is the mean age of air.

The analytical model of the mean age of air depend as outlined below on the applied strategy for the tracer gas injection.

3.1 Tracer decay technique

Using the tracer decay technique the mean age of air ($\langle A \rangle$) within the room and the local mean age of air (A_p) at a point p can be computed using the equations²:

$$\langle A \rangle = Q/V \int_0^{\infty} \tau C_e(\tau)/C_e(0) d\tau, \text{ and} \quad (2)$$

$$A_p = \int_0^{\infty} \tau C_p(\tau)/C_p(0) d\tau \quad (3)$$

where $C(\tau)$ is the tracer gas concentration at time τ , and $C(0)$ is the concentration at $\tau=0$. Subscript e refers to the exhaust air, and subscript p to a point p. V is the indoor volume, and Q is the exhausted airflow. For convenience the zeroth moment of the measured concentration vs time about the origin is denoted MO, where²

$$MO = \int_0^{\infty} C(\tau) d\tau \quad (4)$$

Likewise the first moment is denoted M1, where²

$$M1 = \int_0^{\infty} \tau C(\tau) d\tau \quad (5)$$

Assuming a complete mixing at $\tau = 0$, it is noted that

$$MO_e = (V/Q) C_e(0) \quad (6)$$

Substituting equation 4,5 and 6 into equation 2 and 3 the mean ages may be expressed as follows³:

$$\langle A \rangle = Ml_e / MO_e, \text{ and} \quad (7)$$

$$A_p = MO_p / C_p(0) \quad (8)$$

3.2 Tracer pulse technique

Using the technique of delivering a tracer pulse by the supply air the mean ages may be computed using the equations³:

$$\langle A \rangle = \int_0^{\infty} \tau C_e(\tau) d\tau / \int_0^{\infty} C_e(\tau) d\tau = Ml_e / MO_e, \text{ and} \quad (9)$$

$$A_p = \int_0^{\infty} \tau C_p(\tau) d\tau / \int_0^{\infty} C_p(\tau) d\tau = Ml_p / MO_p \quad (10)$$

If m is the amount of tracer gas released as a pulse it is noted that $m = Q MO_e$.

3.3 Tracer step-up technique

Delivering the tracer by the supply air and using the step-up technique the mean ages of air can be computed using the equations⁵

$$\langle A \rangle = Q/V \int_0^{\infty} (1 - C_e(\tau) / C_e(\infty)) d\tau, \text{ and} \quad (11)$$

$$A_p = \int_0^{\infty} (1 - C_p(\tau) / C_p(\infty)) d\tau \quad (12)$$

where $C(\infty)$ is the equilibrium concentration, and $C_e(\infty) = q/Q$ where q is the flow rate of the tracer gas. Two quantities NO and NI are defined for convenience as follows:

$$NO = \int_0^{\infty} (1-C(\tau)/C(\infty)) d\tau, \text{ and} \quad (13)$$

$$NI = \int_0^{\infty} \tau (1-C(\tau)/C(\infty)) d\tau \quad (14)$$

Normalizing the measured concentration to $C(\infty)$ it is noted that the quantities NO and NI are the zeroth and the first moment about the origin of the complementary normalized concentration vs time, respectively. It is noted⁴ that the nominal time constant τ_n of the ventilation system may be obtained by

$$t_n = V/Q = NO_e \quad (15)$$

By substituting equation 13,14 and 15 into equation 11 and 12 the ages may be computed as follows:

$$\langle A \rangle = NI_e / NO_e, \text{ and} \quad (16)$$

$$A_p = NO_p, \quad (17)$$

4. ESTIMATING THE PARAMETERS

In the field the sampling period of an experiment may often be restricted so the measured concentration vs time is obtained only for a given time interval τ_0 . Theoretically, however, an integration of the concentration vs time is needed for $\tau \rightarrow \infty$. By the menu-driven software of the present study this integration over the interval $0 < \tau < \infty$ may be approximated firstly by

curvefitting, secondly by integrating the extrapolated fitted curve. When using the tracer decay or the tracer pulse technique the fitting of the data obtained from a point p is by the function $C_p(\tau) = C \exp(-\tau/\tau_p)$, where τ_p is a "local time constant". When using the tracer step-up technique the fitting is by the function

$$C_p(\tau) = C_p(\infty)(1 - \exp(-(\tau + \beta_p \tau_p)/\tau_p)) \quad (18)$$

where β_p is a possible off-set. In case of no off-set it may be noted that $\tau_p = \tau_p$, otherwise $\beta_p \tau_p$ indicate a delay in the stimulus-response relationship of the experiment. As an option of the software the moments mentioned may also be estimated on only a preselected time interval within τ_0 in case of an unacceptable low coefficient of regression of the fitted function.

5. TEST RESULTS

In a field study the ventilation process of the non-occupied lecture hall ($V = 400\text{m}^3$) shown in fig. 2 was characterized by the tracer step-up method. The nominal flow rate of the balanced mechanical ventilation system (supply/exhaust) was $Q = 0.22\text{m}^3/\text{s}$ and the air temperature of the supply air was 20.0°C . The tracer gas was delivered ($q = 5.3 \cdot 10^{-6}\text{m}^3/\text{s}$) in the supply duct, and the concentration vs time was sequentially (45 sec step period) measured at 5 different points (No. 2-6) in the room, and at a point (No. 1) in the exhaust duct. Additionally the air temperature was measured at some of the points.

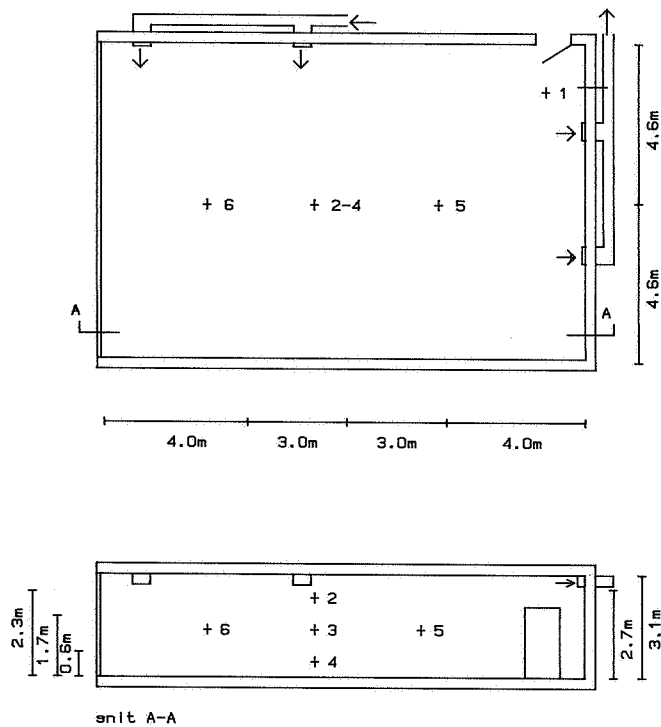


Fig. 2. The lecture hall where the test was carried out.

As an example the measured concentration vs time at point No.3 is plotted in fig 3. In the plot is also shown the function fitted to the data. For each of the points measured the estimated parameters of the fitted function are listed in table 1 as well as the estimated moments N_0 and N_1 .

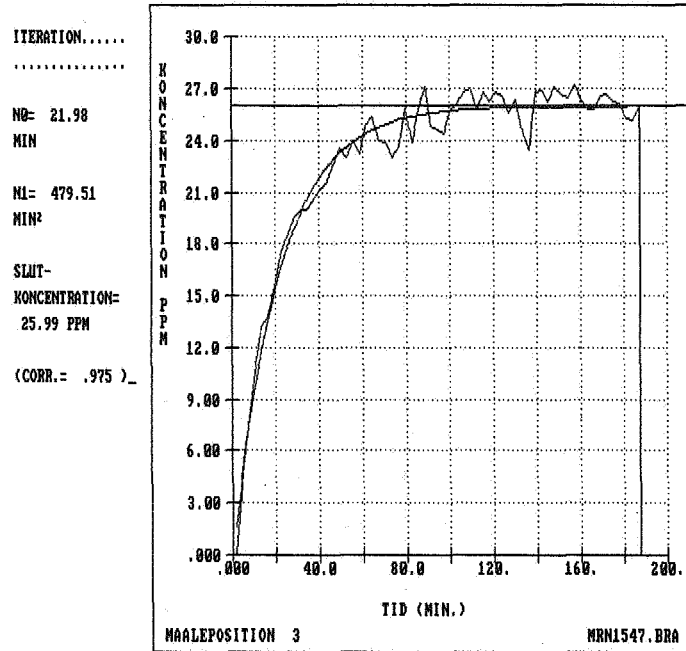


Fig. 3 Step-up test in point No. 3.

Point No.	$C_p(\infty)$ ppm	τ_p h	β_p	$\tau_p \beta_p$ h	R^2 a)	NO_p h	NI_p	Air temp ^o C
1	26.4	0.51	0.094	0.047	0.982	0.56	0.29	21.0
2	24.0	0.34	0.004	0.002	0.854	0.34	0.11	20.8
3	26.0	0.36	0.004	0.002	0.975	0.37	0.13	-
4	25.7	0.48	0.054	0.025	0.957	0.50	0.24	21.3
5	26.6	0.44	0.048	0.021	0.985	0.46	0.20	-
6	27.4	0.42	-0.114	-0.048	0.954	0.38	0.16	-

Table 1. Estimated parameters of a tracer gas step-up field study. a: coeff. of regression.

From table 1 the mean age of the air in the room is calculated (point No. 1) as $\langle A \rangle = N1_e / NO_e = 0.51$ h, and the exhausted flow rate of air is estimated to be $Q = q/C_e(\infty) = 0.20 \text{ m}^3/\text{s}$. The time constant of the room is estimated to be $\tau_n = NO_e = 0.56$ h. The air exchange efficiency is estimated to be $\langle \epsilon_a \rangle = NO_e^2 / 2 N1_e = 0.54$.

6. DISCUSSION

The approach of age analysis in characterizing the ventilation process has mainly⁴ been used in small spaces with relatively simple geometry and ventilation arrangement. Test results are available from experiments in the laboratory², and as recently reported⁶ the approach may also be useful in field studies, including large spaces. The results of the present field study were obtained in a non-occupied room at near isothermal conditions with a temperature difference between supply and room of less than 1.3° C. The time constant of the room was estimated to be 0.56 h. At positions within the room the estimated "local time constant" ranged 0.34-0.51 h. As listed in table 1 the estimated delay of the stimulus-response relationship of the experiment ranged (-0.048;0.047 h) causing a difference ranging 0-0.05 h between τ_p and NO_p . Within the room the estimated local mean age of air ranged 0.34-0.50 h, and the mean age of the exit air was 0.56 h. On the average the ventilation process of the non-occupied room may be characterized as almost complete mixing, the estimated air exchange efficiency being 54%. This conclusion, however, may not be valid for the occupied room due to convective currents from people. Finally it is emphasized that the portable unit may also be useful in documenting the indoor air pollution.

7. CONCLUSION

A portable computerized unit is described for documenting the ventilation process by the approach of age analysis. The software of the unit is menu-driven, designed to be operated by computer non-experts. By the portable unit the air exchange efficiency of a non-occupied mechanically ventilated lecture hall was estimated to be 54%.

ACKNOWLEDGEMENT

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VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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POSTER P3

ADVANTAGES OF MICROCOMPUTER SUPPORT FOR AIR CHANGE
MEASUREMENTS

F.D. HEIDT¹ and H. WERNER²

¹Dept. of Physics, Univ. of Siegen, 5900 Siegen, F.R.G.

²Siemens AG, Medical Engg. Group, 8520 Erlangen, F.R.G.

SYNOPSIS

Air change rates are measured by an IR-gas-analyzer coupled with a microcomputer which is programmed to control measurements as well as data acquisition and -evaluation. The implemented programs provide an instant access to results. The experimental equipment is installed in compact form on mobile units.

Measurements have been taken in a university laboratory by using the decay- and constant-emission-method to examine air change rates under various conditions. Typical results are presented and show where each of the two methods is more appropriate. The advantages of microcomputer usage are discussed.

INTRODUCTION

The air change rate $Q = n \cdot V$ between an enclosure of effective volume V and its environment or the corresponding volumetric air change rate n are among the less understood aspects of building design and performance. They depend on building construction, meteorological parameters as well as on occupant's behaviour [1]. On the other hand, n -values are prerequisite to estimate the heating demand of buildings [2] and to predict indoor air quality and humidity [3]. Measurements of tracer gas concentrations can be used to calculate n -values according to three procedures [4]: A) concentration decay, B) constant emission and C) constant concentration of the gas. Two of them (A,B) have been implemented and investigated in detail.

The main objective of this work were improvements of experimental procedures, and especially, of data acquisition and evaluation techniques by combining tracer gas measurements with a microcomputer. Measurements of air change rates have been conducted in a university laboratory. They served only as illustrating examples showing the typical range of measuring values for the given situations. Special emphasis is given on data analysis and the estimation of errors as well as on the comparison of methods A and B.

THEORETICAL ANALYSIS OF MEASUREMENTS

A small amount of an inert tracer gas is well-mixed with room air and its concentration values are recorded as a time series.

Then, conservation of mass (continuity equation) requires

$$V \frac{dc}{dt} = (c_A - c) \cdot V \cdot n + F \quad (1)$$

where $V(\text{m}^3)$ is the effective volume of the enclosed space, $n(\text{h}^{-1})$ air change rate, $F(\text{m}^3/\text{h})$ flow rate of tracer gas, c (e.g.: ppm) tracer concentration and $t(\text{h})$ time. Subscript A denotes ambient air. This first order differential eqn. (1) has to be solved for the initial condition:

$$c(t=0) = c_0 \quad (2)$$

Using a tracer gas which normally doesn't exist in the environment:

$$c_A = 0 \quad (3)$$

results in:

$$c(t) = c_\infty + (c_0 - c_\infty) \exp(-nt) \quad (4)$$

with the dimensionless tracer gas injection rate c_∞ :

$$c_\infty = F/(V \cdot n) \quad (5)$$

A suitable tracer gas has to meet a set of requirements [5] and leads to a restricted number of options. They have been compared with respect to accuracy [6]. Nitrous oxide (N_2O) emerges for a number of reasons as a favourable candidate and has been chosen as tracer in this case.

Method A - constant decay ($c_\infty = 0$) - results in:

$$c(t) = c_0 \cdot \exp(-nt) \quad (6)$$

whereas method B - constant emission ($c_\infty > 0$) - yields the more general solution of eqn. (4).

For method A the air change rate n is calculated in a straight-forward manner from eqn. (6):

$$n = \frac{1}{t} \ln \frac{c_0}{c(t)} \quad \text{or} \quad n = \frac{1}{\Delta t} \ln \frac{c(t)}{c(t+\Delta t)} \quad (7)$$

where t and Δt are any values of time and time increment during the measuring period. For method B the value of n can be determined from eqn. (4) only by numerical iteration or by differentiation of eqn. (4) with respect to time from:

$$n = - \frac{d^2c}{dt^2} \bigg/ \frac{dc}{dt} \quad (8)$$

The accuracy in determining n depends for both methods on the observation errors of the parameters:

$$x_1 = c(t), \quad x_2 = c_0 \quad \text{and} \quad x_3 = c_\infty \quad (9)$$

where we consider time t to be measured exactly. Then, the Gaussian law of error propagation results in:

$$(\delta n)^2 = \sum_1^3 \left| \frac{\partial n}{\partial x_i} \delta x_i \right|^2 \quad (10).$$

δ denotes deviation of a variable from its mean value. For method A which is independent on $x_3 = c_\infty$ we simply put $x_3 = \delta x_3 = 0$.

As mentioned above, the function $n(x_1, x_2, x_3)$ is not generally available as an explicit analytic expression. We use eqns. (9), (4) and (5) and define an implicit function f of n, x_1, x_2 and x_3 :

$$f(n, x_1, x_2, x_3) = x_1(t) - x_3 - (x_2 - x_3) \exp(-n \cdot t) = 0 \quad (11)$$

Thus, partial derivatives $\partial n / \partial x_i$ in (10) can be substituted by:

$$\frac{\partial n}{\partial x_i} = - \frac{\partial f}{\partial x_i} / \frac{\partial f}{\partial n}, \quad i = 1, 2, 3 \quad (12)$$

and the squared error $(\delta n)^2$ becomes:

$$(\delta n)^2 = \left(\frac{1}{\partial f / \partial n} \right)^2 \cdot \sum_1^3 \left| \frac{\partial f}{\partial x_i} \cdot \delta x_i \right|^2 \quad (13)$$

This relationship has been evaluated for the general case. For the asymptotic value of the squared error we find finally:

$$\left(\frac{\delta n}{n} \right)^2 = \left(\frac{\delta c}{c_\infty} \right)^2 + \left(\frac{\delta V}{V} \right)^2 + \left(\frac{\delta F}{F} \right)^2 \quad (14).$$

If we restrict our attention to method A error estimation for $(\delta n)^2$ is immediately obtained by differentiation of n in eqn. (7):

$$(\delta n)^2 = \frac{1}{t^2} \left[\left(\frac{\delta c}{c} \right)^2 + \left(\frac{\delta c_0}{c_0} \right)^2 \right] \quad (15)$$

$c_0, \delta c_0$ and δc are assumed as constant values. The error δn then decreases rapidly with increasing time t . However, as soon as $c(t)$ becomes small itself, the error δn increases again. The optimum measuring time τ is in the proximity of $1/n$. Because method A is normally used only for medium-to-low air change rates the available measuring time is always large enough to avoid a time domain with increasing error.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The experimental equipment consists of three main components:

- gas analyzer with RS 232 interface
- microcomputer with printer-plotter

- gas injection apparatus
as well as a bottle with compressed calibrated gas.
They are installed in compact form on mobile test
units (Fig. 1).

A key-component of the measuring system is the
commercially available nondispersive one-beam IR gas
analyzer UNOR 6N, which detects low concentrations
(1 ppm to 100 ppm) of the tracer gas nitrous oxide
(N₂O). Its physical principles and main features are
described in detail elsewhere [7,8].

A specially designed RS 232 interface unit enables
coupling of a microcomputer with the N₂O-analyzer
which is normally equipped with an analog data output.

The microcomputer is an ABC 24 of AI Electronics
Corporation, Tokyo, Japan. It is based on a Z 80 A
microprocessor with 64 kB RAM, two floppy disk drives
(5 1/4 inch, double-side, double-density) and a 12-inch
high resolution screen. The ABC 24 is connected with a
printer-plotter which is controlled via another RS 232
interface.

The gas injection apparatus is very simple (Fig. 2):
It consists of a storage bottle of compressed gas with
throttling valve followed by a pressure vessel of
known volume and a flexible tube connected with a
mixing fan which can be moved freely.

For constant emission measurements the tracer gas
streams through a rotameter and its flow rate is
manually controlled by means of an adjustable quenching
element at the tube. Calibration gas flows directly
from the stock bottle to the gas intake of the
analyzer.

Running an experiment is essentially simple and con-
sists of the following sequence of operations:

- 1) calibration of the analyzer
- 2) definition and/or preparation of measuring conditions
- 3) measurement control and data handling.

Microcomputer programs have been developed to support
and to facilitate these points [7]. The first one can
be executed by using the program SIOINT which
activates the serial input-output interface between
analyzer and microcomputer. Measured values are dis-
played on screen every 0,2 or 2,0 second.

The second point is of special importance for method B
where a suitable value of initial concentration c_0 and
gas flow rate F has to be selected in order to achieve
a favourable resolution for a given measuring range
within a desired time period t_M . For method A only c_0
and t_M have to be selected.

Point 3 is supported by a program MEASMT which defines
all variables and operation parameters of measuring
procedure and data management. The program establishes

data files on the floppy disk where all variables, parameters and measuring values are stored. Basically, two measuring modes have been realized: Time-dependent and value-dependent mode (TDM, VDM). TDM means that measured values are taken and stored every given time step. VDM means that the decision whether measured data are stored or not depends on their relative difference to the preceding values. This reduces the required capacity for data storage without omission of significant information.

All programs are intended to be user-friendly by an interactive part for the input of required variables and program control parameters from keyboard. After the input has been completed programs run automatically and the output of results appears on the screen and/or printer-plotter according to the choice of a specific control parameter. Results include tabular listings and graphic presentations of $c(t)$.

DATA EVALUATION

Principle of data analysis is the approximation of measured concentrations $c_k(t_k)$ - the index k varies from 1 to N , where N is the total number of measurements - by an exponential expression:

$$c(t) = A_0 + A_1 \cdot \exp(-A_2 \cdot t) \quad (16)$$

A_0, A_1 and A_2 are numerical parameters fitting eqn. (16) to measured data by means of the Gaussian least squares method. Comparison of eqns. (16), (4) and (5) yields:

$$A_0 = c_\infty = F/(nV) \quad (17)$$

$$A_1 = c_0 - c_\infty \quad (18)$$

$$A_2 = n \quad (19)$$

The asymptotic value A_0 is zero for method A and the air change rate n is determined unequivocally from eqn. (19) or A_2 , respectively. For method B, however, n can be independently derived at least from eqns. (17) and (19). This duality in determining n provides a good test for credibility of results.

Air change rates have been numerously measured in a somewhat leaky university laboratory ($V = 42 \pm 2 \text{ m}^3$) for winter conditions and three different cases [7]:

- (1) closed door, closed window $(0.5 \leq n(\text{h}^{-1}) \leq 1.4)$
- (2) open door, closed window $(2.4 \leq n(\text{h}^{-1}) \leq 18.0)$
- (3) closed door, tilted window $(6.2 \leq n(\text{h}^{-1}) \leq 23.2)$

The numbers in brackets above on the right-hand-side give the range of observed values for each case. Large scattering of n -values is attributed to varying meteorological parameters such as wind- and temperature-induced pressure difference between the considered room and its environment. These parameters have not been investigated further within the context of this work.

DISCUSSION OF TEST RESULTS

Figures 3 and 4 show illustrative examples for case (1) and present concentration profiles measured according to method A and method B. Recorded concentration decay follows extremely well the approximation function resulting in a rather small error of the air change rate ($n = 1.30 \pm 0.03 \text{ h}^{-1}$). If under similar conditions a constant flow rate $F = 8.2 \cdot 10^{-3} \text{ m}^3 \text{ h}^{-1}$ is applied, concentrations increase with time and follow also fairly well a corresponding approximation function (figure 4). Air change rate is determined from eqn. (19) and yields a somewhat larger error: $n = 1.15 \pm 0.13 \text{ h}^{-1}$. If determined independently from eqn. (17) the resulting n -value is in good agreement with the preceding figure: $n = 1.22 \text{ h}^{-1}$.

In case (2), at first a uniform tracer gas concentration is established in the measuring room. Then the door is opened and concentration decreases. The latter situation is illustrated in figure 5 for conditions of rapid air renewal: $n = 12.7 \pm 0.3 \text{ h}^{-1}$. Concentration fluctuations around the approximation function are quite sizeable. They show that at the beginning of the experiment the composition of fresh air and room air is not perfectly mixed but consists of large eddies with slightly different concentrations. Due to the rapid air change very low concentrations are reached a few minutes after the beginning of the experiment. This lowers the accuracy of data evaluation and, therefore, constant emission method B is recommended for such conditions instead of concentration decay method A which was used here.

Method B has been applied to case (3) and results are presented in figure 6. A constant flow rate $F = 7.7 \cdot 10^{-3} \text{ m}^3 \text{ h}^{-1}$ of tracer gas is mixed with air of the measuring room (closed door and window) and concentration increases. Then, the window is tilted and air change rate rises rapidly from $n = 1.10 \pm 0.14 \text{ h}^{-1}$ during the first 600 s to $n = 17.4 \pm 1.3 \text{ h}^{-1}$ after 900 s, a process which is accompanied by a sudden decay of concentration. Because theoretical analysis is based on constant n -values the transient range $600 \text{ s} \leq t \leq 900 \text{ s}$ cannot be evaluated. Determination of n for the domain $900 \text{ s} \leq t \leq 1800 \text{ s}$ from eqn. (17) instead of eqn. (19) results in $n = 18.3 \text{ h}^{-1}$, a value which is situated within the expected limits of error.

A very interesting result is presented in figure 7 which shows the tracer gas profile for a method B measurement in the case of varying window positions in an adjacent room. The alterations of the concentration profile are retarded in time with respect to changing window positions but the interdependence is quite obvious. This shows the importance of interzonal air exchange rates which cannot be treated with the simple 1-node-model discussed in this paper.

SUMMARY AND CONCLUSION

A moveable measuring station for air change rates has been constructed and tested in a university laboratory under various conditions. The measuring procedure provides a quick access to results with a preparation phase of typically 15 minutes and measuring periods between 15 and 30 minutes. Evaluation and output of results takes less than 5 minutes.

Two methods are examined: Concentration decay (A) and constant flow rate (B). Method A is very well suited for small n-values (typically $\leq 6 \text{ h}^{-1}$), whereas method B seems to be more appropriate for larger n-values, because too rapid concentration decays and corresponding short measuring periods are avoided by suitable dimensioned injection of tracer gas. As an additional advantage of this method, n-values can be determined by two different ways, and thus offer the opportunity to compare and to test credibility of results.

The main advantage for the two measuring methods A and B comes due to the capabilities of microcomputers. They help to perform thoroughly and quickly the following tasks:

- Preparation of measurements: Calibration. Choice of initial concentration, measuring time, injection rate (if required).
- Control of measurement: Time steps, interrupts, conditions for ending.
- Automatic display, graphic presentation, recording of measuring parameters and values.
- Immediate and fast evaluation of measurements with complete presentations from initial conditions up to the results.
- Theoretical error analysis as well as statistical evaluation procedures for measured data.
- Evaluation of a reduced data set only if so required by failings of instruments or other obviously erroneous effects.

Moreover, a microcomputer is able to perform even more complicated measuring and evaluation procedures as they are required for constant concentration measurements

or for a determination of interzonal air change rates between different rooms of a building. In addition, correlation analysis of air change rate and other relevant meteorological or user-specific parameters can be done easily and without much effort in time. We conclude finally that the capabilities of traditional measuring methods are enhanced by the usage of micro-computers and that they are even mandatory for any more sophisticated measuring and evaluation method to obtain air change rates.

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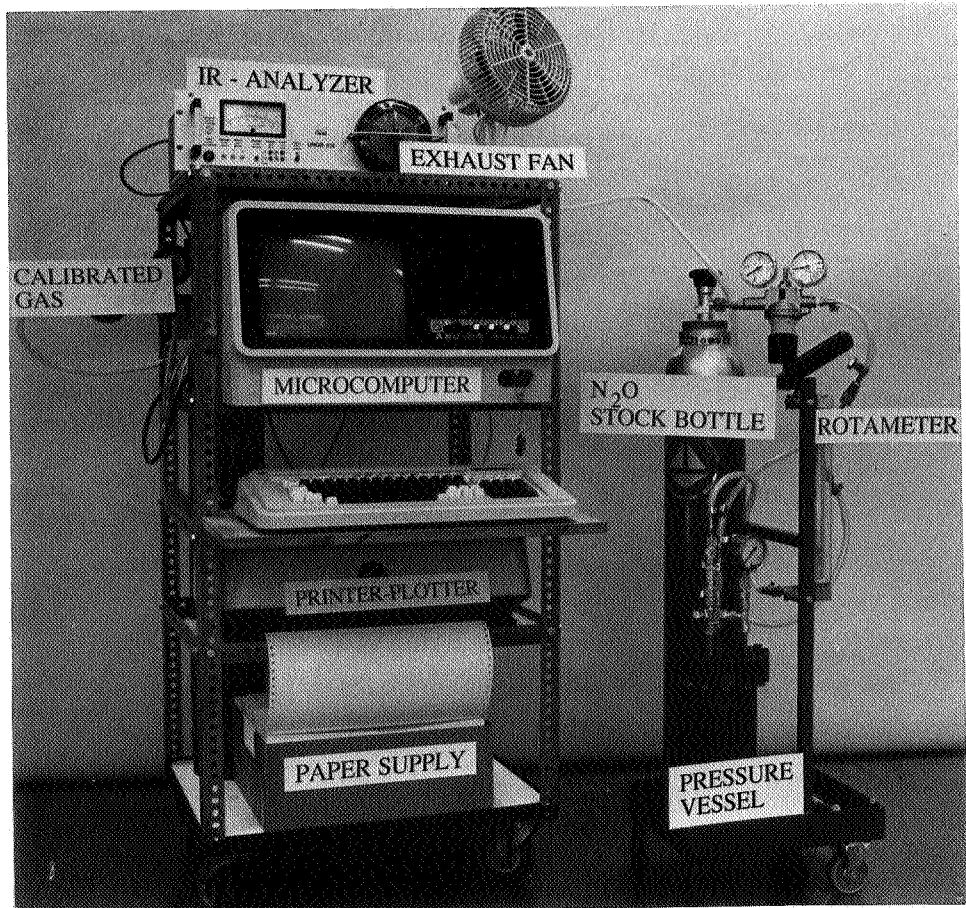


Fig. 1: Measuring unit's configuration. Left-hand side: IR-analyzer with RS 232 interface, gas exhaust fan, calibrated gas, microcomputer and related equipment. Right-hand side: gas injection apparatus consisting of stock bottle, pressure vessel, rotameter and related armatures.

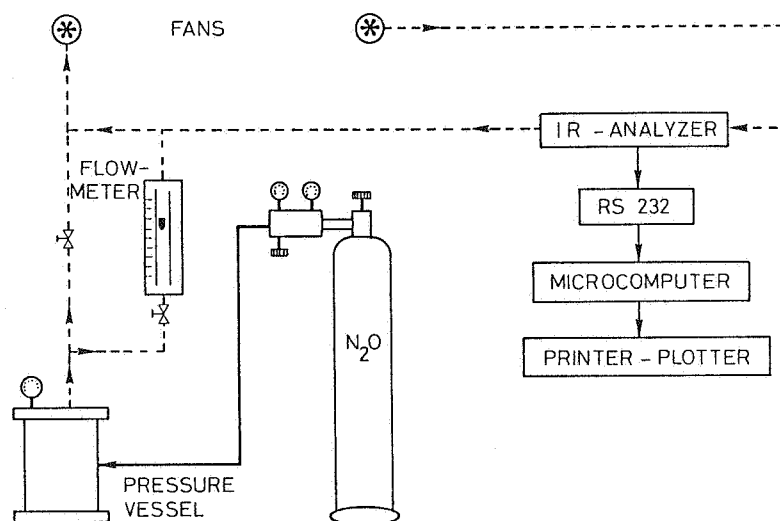


Fig. 2: Schematical illustration of measuring system and gas injection apparatus.

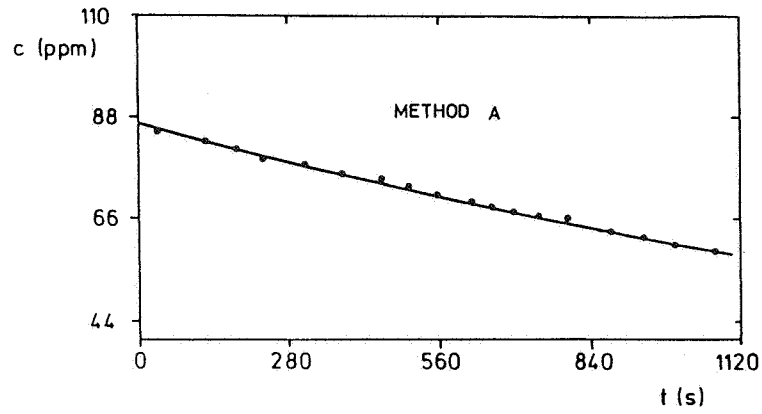


Fig. 3: Tracer gas concentration decay for case (1) - measurements: closed door and window: $n = 1.30 \pm 0.03 \text{ h}$ (measurements: points, approximation: line).

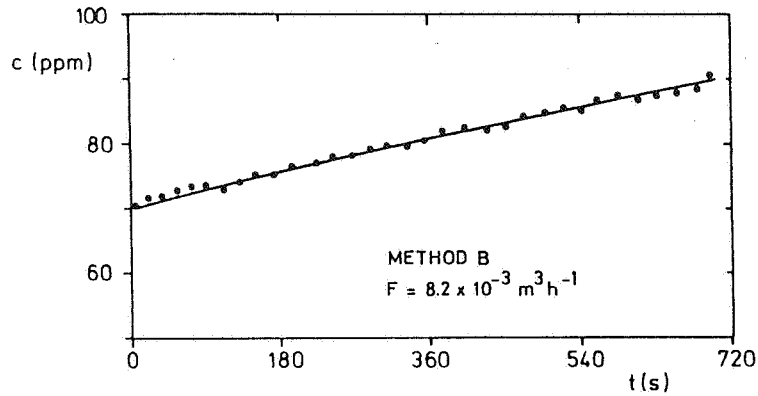


Fig. 4: Increasing tracer gas concentrations for case (1) - measurements: closed door and window: $n = 1.15 \pm 0.13 \text{ h}^{-1}$ (measurements: points, approximation: line).

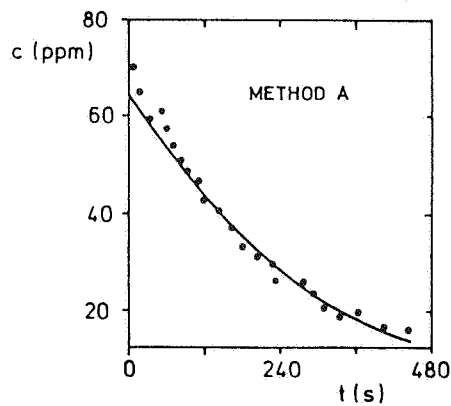


Fig. 5: Rapid concentration decay for case (2) - measurements: open door and closed window: $n = 12.7 \pm 0.3 \text{ h}^{-1}$ (measurements: points, approximation: line).

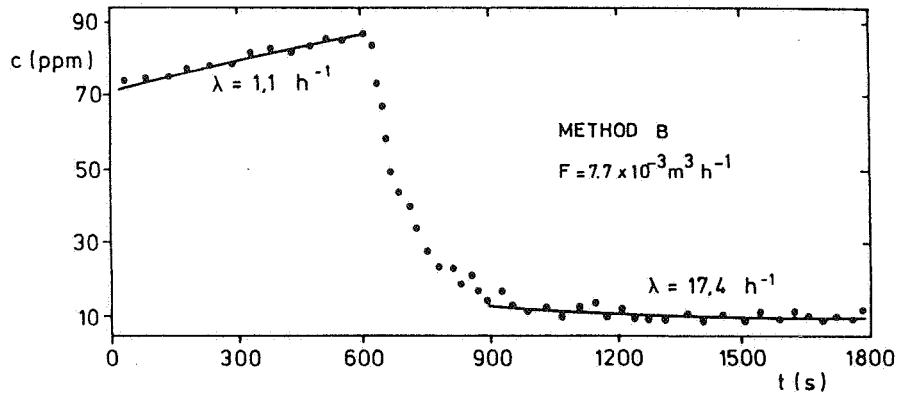


Fig. 6: Concentration profile for case (1)/case (3)-measurements: closed door and window/closed door and tilted window. During the time interval [600 s, 900 s] the air change rate increases from $n = 1.1 \text{ h}^{-1}$ to $n = 17.4 \text{ h}^{-1}$ (measurements: points, approximation: lines).

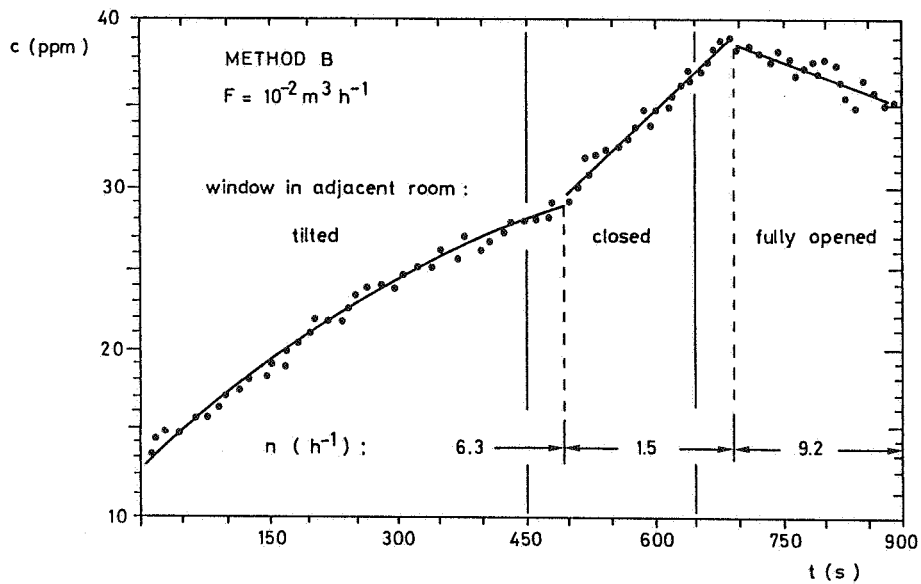


Fig. 7: Concentration profile for case (1)-measurements: closed door and window. A window in the adjacent room is tilted, closed or fully opened at the indicated moments of time. With some time lag the air change rate is significantly altered by these changed window positions (measurements: points, approximation: lines).

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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POSTER P4

VENTILATION AND LEAKAGE MEASUREMENTS
IN INDUSTRIAL BUILDINGS

J. P. LILLY

British Gas plc
Research & Development Division
Watson House Research Station
London, SW6 3HN.

SYNOPSIS

It has been estimated that 15% of the energy used for building services in the United Kingdom is consumed in industrial buildings. A large proportion of this is thought to relate to infiltration and ventilation. There has been very little information produced concerning infiltration rates in industrial buildings because of the difficulty in making accurate measurements.

During the past three years, British Gas has made ventilation and building leakage measurements in a number of industrial and other large buildings in the UK. These include detailed measurements in a school, industrial laboratories, warehouses and industrial production units. These employ a variety of different construction types, heating systems, and provisions for ventilation.

Detailed measurements have been made of ventilation rates and natural air infiltration using the British Gas "Autovent" measuring system and simple tracer gas decay tests. Building leakages were measured using "Watson House Leakage Testers". Some of the buildings were draught-sealed and re-measured to assess the effectiveness of certain retrofit measures.

This paper discusses the results of the measurements made with respect to the building type and construction, the sensitivity of the building to weather driven air infiltration and the effects of heating and ventilation systems on the ventilation heat losses. The effectiveness of some retrofit sealing methods on the modification of building ventilation rates and heat losses is also discussed, along with some examples of the cost effectiveness of these measures.

MEASUREMENT EQUIPMENT

British Gas has developed much equipment for the measurement of building air leakage and ventilation.

The Watson House leakage testers (See Fig.1) were designed for the pressurisation testing of domestic dwellings with maximum flow rates of $1.25\text{m}^3\text{s}^{-1}$ each at 50Pa. Up to four of these testers were used in parallel in order to obtain leakage data for tests 5,6,7,8 and 9. (See Table 1) A wind generator (12.5HP) was used for the pressure testing of the industrial laboratory (tests 1&2) up to a pressure of 20Pa with flow rates up to $20,000\text{m}^3/\text{hr}$. A purpose built leakage tester for large buildings is now in operation to generate 50Pa pressure differences at flow rates of up to $150,000\text{m}^3/\text{hr}$ (Fig.2).

Ventilation measurements were predominantly made with the British Gas Autovent system, (Fig.3) using the constant concentration method. Alternatively decay tests were used (automated decay tests were made possible by using the Watson House mobile ventilation laboratory. (Fig.4)).

RESULTS

Table 1 shows the results of ventilation and pressurisation tests performed on seven large buildings. These comprise two old industrial buildings (a warehouse and laboratory), a school, and four modern factory units. The volume of these buildings vary from 660 to 12,600m³. The age and construction of each building is briefly described in Table 1 together with the results of building leakage and ventilation tests. The detail of the ventilation measurements in each building varies considerably, so the available data has been reduced to each buildings sensitivity to stack and wind driven infiltration. These are expressed in airchanges per hour per ms⁻¹ wind speed and K₁ stack effect. In tests 3,4 and 6 measurements not performed over a wide enough range of temperature difference to enable stack driven infiltration rates to be determined. The infiltration rates in test 7 were not measured directly, but were obtained from a combination of building leakage data and calculations using the British Gas ventilation model "VENT 2."

The building leakage data is presented using a reference pressure difference of 50Pa between the inside and the outside of the building. Not all the results were obtained using equipment capable of producing the required flow rate and pressure difference. In these cases, a quadratic curve fit to the experimental pressurisation curve has been obtained. The quoted figures marked thus (*) are extrapolations based on the quadratic equations fitted to the experimental curves.

Figure 5 shows a graph which compares the measured infiltration sensitivities to wind speed and stack effect and the measured leakage rates obtained from the pressurisation tests.

DISCUSSION (See Table 1)

Building A was an industrial laboratory built in the 1950's with a very leaky construction of breeze block and metal cladding. Most of the leakage in test 1 was therefore due to a large leakage path through the cavity. This was easily sealed with polyurethane foam sealant at a cost of £175. (£35 materials, £140 labour @ £10/hr (includes draught-stripping doors)). The results of test 2 show that after sealing the infiltration reduced by a factor of 2.6, and the leakage reduced by a factor of 3.0. These measures would reduce the typical heating season infiltration rate from 2.6 ac/hr to 1.0 ac/hr⁵. The high level of ventilation in this laboratory was not necessary and no problems with air quality resulted from these sealing measures. This direct reduction in ventilation represented an annual saving of £163 in gas heating costs (for an average 210 day 7°C heating season). The draught sealing measures therefore had an approximate simple payback period of 1.1 years. (The efficiency of the gas heating plant is taken as 70%).

The reduction of building air leakage was slightly larger than the reduction in infiltration. This is probably due to the changes in leakage distribution of the building before and after sealing. A large proportion of the building's leakage was concentrated at a height of 3m (at the junction between the cavity wall and the upper glazed area). The sealing of this major leakage source was likely to significantly change the infiltration characteristics of the laboratory.

Building B was an industrial warehouse, built before 1900. It is a very leaky building with badly fitting loading bay doors, and considerable gaps at the eaves. The multiple pitch roof was also in bad repair and of leaky construction. The specific ventilation rate was the highest of any of the buildings tested⁷. As this was also the largest building tested, it represents an exceptionally high level of air leakage and infiltration. Pressurisation fans of sufficient capacity were not available to perform leakage tests at the time of ventilation measurements.

Building C was a small, open plan school built in 1974, with a mechanical ventilation system providing 3 airchanges per hour². It had an infiltration rate of 0.22 airchanges per ms⁻¹ wind speed. A pressurisation test was not performed.

Building D was a modern factory unit built in 1981 with insulation in the walls and roof. Building E was built at the same time, but to a modern low energy specification. Building D had a roof vent which increased the ventilation rate by 20% with a temperature difference of 10.5°C, although only a 5% increase in leakage was observed with the vent open⁶. A large proportion of the total leakage was due to a badly fitting loading door. Sealing the loading door resulted in a 45% reduction in infiltration and air leakage. In practice, a good quality loading door would cost £280 more than the door fitted. The resultant reduction in seasonal infiltration from 1.4 to 0.8 ac/hr would save £127 per annum in gas used for heating the building over a typical heating season. This single measure would therefore have a simple payback period of 2½ years.

Building E only had its air leakage measured on site. The ventilation rates have been calculated by the British Gas ventilation computer model VENT 2. The values marked on Table 1 are derived from these calculations. Particular attention had been paid to the air tightness of this factory unit during construction, including the use of a well-fitting loading bay door. The calculated specific ventilation rates are approximately 20% lower than building D when the loading door was sealed. The air leakage was 11.6 airchanges at 50Pa, which is similar to the air leakage of an average UK house⁹. It is therefore probable that the air leakage of factory units like building E could be further reduced with relative ease.

Buildings F and G were modern low energy factory units of 6000m³ volume with attention paid to the air tightness during construction which included the installation of well

fitting roller loading bay doors. The specific ventilation rates are quite low, as would be expected in buildings of this size and construction. Although the measured infiltration rates were identical for both units, their leakage varied by 5000 m³/hr at 50Pa. This occurred because the more leaky of the two adjacent factory units was in the lee of the tighter factory unit when the wind was in the prevailing SW direction (as was the case during the bulk of the measurement period). Additional air was drawn into the factory unit by the radiant tube heating system which would increase the ventilation rate during the heating season by up to 0.2 airchanges per hour. A roof vent and extract fan could increase ventilation to 1.2 airchanges per hour if necessary.

The graph in figure 5 shows the relationship between the air leakage at 50Pa and the specific ventilation rate due to wind speed and stack effect for the buildings measured.

It is interesting to note that buildings that were draught sealed (A&D) reduced their infiltration rates in approximate proportion with their air leakage at 50Pa. The greater deviation of building A from the proportional reduction in infiltration with leakage is probably due to the significant changes in vertical leakage distribution caused by the draught-sealing measures used.

As a result of the experience gained in gathering the data, there is strong evidence that the British Gas Autovent system can accurately measure infiltration rates in large open plan buildings 3,4,5,6,8. Larger industrial buildings will require care to ensure uniform mixing of tracer gas for constant concentration measurements. Good agreement between constant concentration tests and concentration decay tests have also been observed⁸.

The larger buildings described in this paper were pressurised to less than 50Pa due to limitations in the capacity of the leakage testing equipment used. From the extrapolated air leakage flow rates given in Table 1 and the range of infiltration/air leakage ratios shown in figure 5, it is unlikely that it will be practical to maintain 50Pa as a standard pressure difference for estimating the air leakage of buildings larger than 5000 to 10,000m³ in volume. For example, building D was a modern factory unit of 1300m³ volume with an estimated leakage flow rate of 65,000 m³/hr at 50Pa. The larger factory units F and G were built with particular care to reduce air leakage and yet would still require 40,000m³/hr flow rate at 50Pa. The warehouse (Building B) was not pressure tested, but is likely to require at least 900,000 m³/hr flow rate to generate 50Pa across the building envelope. A practical limit of flow rate for pressurisation testing buildings is considered to be 150,000m³/hr. If a standard for pressure testing larger buildings is to be adopted, it will be necessary to reduce the 50Pa pressure difference currently adopted for the measurement of domestic buildings or develop alternative methods of leakage measurement (eg acoustic methods).

CONCLUSIONS

1. The equipment and techniques developed by British Gas can satisfactorily measure ventilation and air leakage rates in large buildings.
2. Measurements of building leakage for the small industrial buildings described in this paper requires pressurisation equipment sufficient to generate flow rates in excess of $65,000\text{m}^3/\text{hr}$ at 50Pa.
3. It will be impractical to pressurise most industrial buildings larger than 5000 to $10,000\text{m}^3$ in volume to a pressure of 50Pa.
4. If a standard for the air leakage measurement of large industrial buildings is required, a lower standard pressure difference across the building envelope will be necessary to avoid the inaccuracies involved with the extrapolation of building leakage/flow rate/pressure curves.
5. Alternative methods of building leakage measurement (eg acoustic) may be necessary for the measurement of particularly large or leaky buildings such as the industrial warehouse referred to in this report (Building B). In this type of building infiltration measurements have proved more practical than leakage measurements which use the techniques available at present.

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TABLE 1

TEST	BUILDING	VINTAGE	CONSTRUCTION (S.A.)	INSULATION	GLAZING
1	A: INDUSTRIAL LAB - SEGAS REF 1,3,5	1950	660m ³ 5m HIGH WALLS x 9m x 14m. 3m BLOCK-LEAKY CAVITY-METAL. 1 PAIR LEADING DOORS CLADDING 1 SHELTERED WALL.	INSULATED ROOF (GENTLY ARCHED) SOLID FLOOR	2m GLAZING ON 3 OF 4 WALLS ABOVE BLOCK & CLAD WALLS.
2	A: AS ABOVE	1950	a)INTERNAL CAVITY LEAKAGE SEALED WITH POLYURETHANE FOAM. b)DISUSED FLUES IN ROOF SEALED. c)DOORS DRAUGHT-SEALED d)DISUSED FRESH AIR FAN SEALED.	AS ABOVE	AS ABOVE
3	B: INDUSTRIAL WAREHOUSE - SEGAS. REF 3,7	C1900	12600m ³ 5.5m VERY LEAKY ASBESTOS SHEET MULTIPLE PITCHED ROOF. 18m LOADING BAY COVERING N WALL. 3 x 3 LOADING BAYS AT N END OF W WALL. 1 x 3m LOADING BAYS ON S WALL.	NONE SOLID FLOOR	HALF GLAZED PITCHED ROOF
4	C: SCHOOL REF 2,4,6,	1974	800m ³ BRICK WALLS FLAT ROOF OPEN PLAN	CAVITY & ROOF	EXTENSIVE
5	D: FACTORY UNIT 1 GWENT. REF 4,6	1981	1300m ³ 5m HIGH WALLS x 12.5m x 21.5m. 21.5m WALLS SHELTERED BRICK-INSULATION - METAL CLAD GENTLY PITCHED ROOF, SINGLE LOADING DOOR.	WALLS + ROOF SOLID FLOOR	ROOF GLAZING LIMITED
6	D: FACTORY UNIT 1 GWENT. AS ABOVE.	1981	AS ABOVE. + LOADING DOOR DRAUGHT SEALED	AS ABOVE	AS ABOVE
7	E: FACTORY UNIT 2 GWENT REF 6	1981	810m ³ 5.5m HIGH WALLS x 10m x 14m. 14m WALLS SHELTERED. BRICK, INSULATION, METAL CLADDING. ATTENTION PAID TO AIR TIGHTNESS.	WALLS + ROOF SOLID FLOOR	ROOF GLAZING LIMITED
8	F: LLANELLI FACTORY UNIT 8 REF.8	1985	6000m ³ 8m HIGH x 30m x 28m. ONE 30m SHELTERED WALL BRICK/INSULATION/METAL CLAD.	WALLS + ROOF SOLID FLOOR	LIMITED ROOF GLAZING
9	G: LLANELLI FACTORY UNIT 7 REF.9	1985	AS ABOVE	AS ABOVE	AS ABOVE

TABLE 1

HEATING SYSTEM	VENTILATION SYSTEM	T SENSITIVITY (h ⁻¹)	WS SENSITIVITY (h ⁻¹)	LEAKAGE @50Pa
2 x WATER/AIR HEAT EXCHANGER, 1 RECIRCULATION. 1 FRESH AIR (DISUSED)	1 FRESH AIR HEATING SUPPLY FAN 4 ROOF EXTRACT FANS (+ 1ac/EXTRACT FAN)	0.65ac/K $\frac{1}{2}$	1.0ac/ms ⁻¹	34,900m ³ /hr (52ac/hr)
AS ABOVE	FOUR ROOF EXTRACT FANS	0.25ac/K $\frac{1}{2}$	0.4ac/ms ⁻¹	11,800m ³ /hr (18ac/hr)
LOCAL DIRECT FIRED HEATERS LOCAL WARM AIR HEATERS	NONE	-	1.4ac/ms ⁻¹	-
4 ZONE WARM AIR H.W. H.W. COIL H&V SYSTEM	SUPPLY/RECIRCULATION EXHAUST H&V SYSTEM 3ac/hr 4 EXTRACT FANS IN TOILETS (10ac/hr LOCAL)	-	0.22ac/ms ⁻¹	-
TEMPORARY ELECTRIC CONVECTION HEATERS	ROOF VENT GIVING VENTILATION INCREASES OF +20% @ T $\frac{1}{2}$ = 3.2, WS = 5 +5% @ Q (50)	0.4ac/K $\frac{1}{2}$	0.44ac/ms ⁻¹	65000m ³ /hr* (50ac/hr)
TEMPORARY ELECTRIC CONVECTION HEATERS	ROOF VENT	-	0.24ac/ms ⁻¹	35000m ³ /hr * (27 ac/hr)
GAS FIRED RADIANT PLAQUE HEATERS	ROOF VENT	INFERRED 0.17ac/K $\frac{1}{2}$	INFERRED 0.19ac/ms ⁻¹	9360 m ³ /hr (11.6 ac/hr)
RADIANT TUBE DRAWING COMBUSTION AIR FROM INSIDE	2 ROOF VENTS WITH EXTRACT FANS.	0.08ac/K $\frac{1}{2}$	0.05ac/ms ⁻¹	40000m ³ /hr* (6.6 ac/hr)
AS ABOVE	AS ABOVE	0.08ac/K $\frac{1}{2}$	0.05ac/ms ⁻¹	35000 m ³ /hr* (5.8 ac/hr)

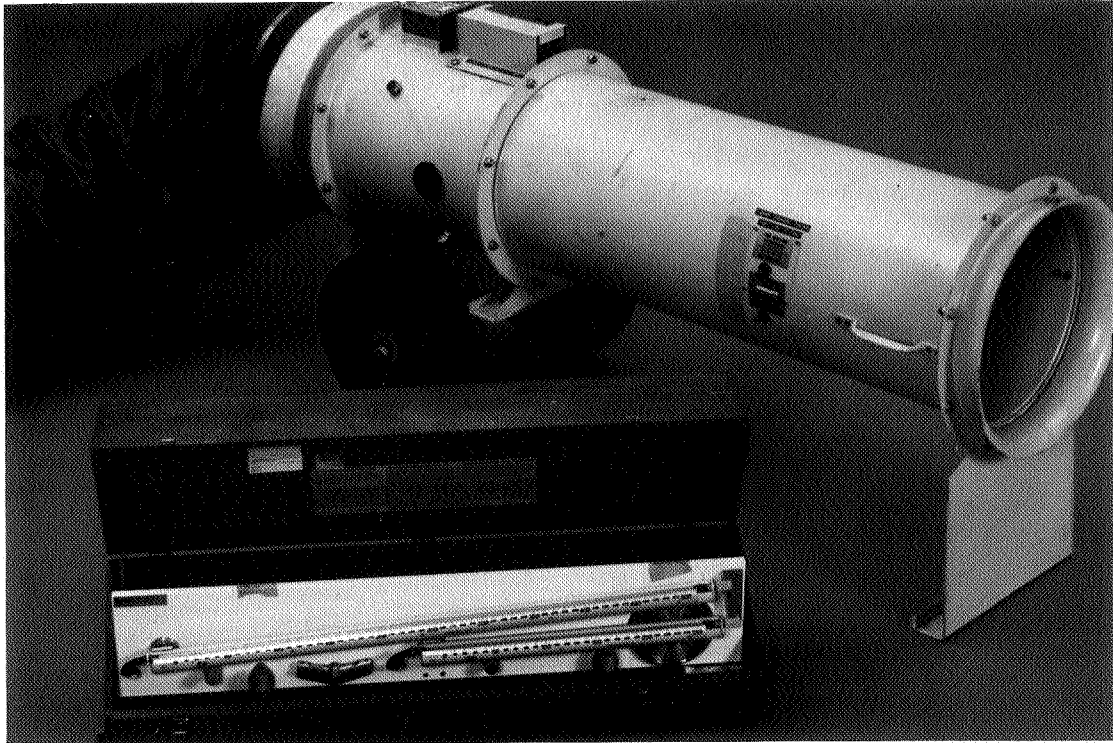


FIGURE 1 : WATSON HOUSE LEAKAGE TESTER

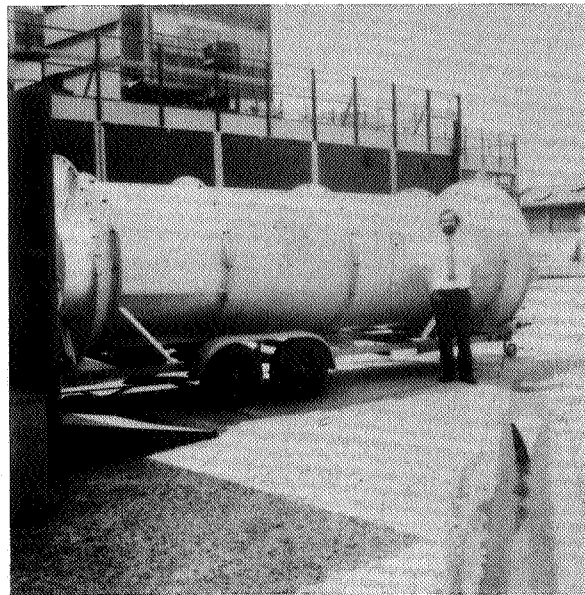


FIGURE 2 : WATSON HOUSE INDUSTRIAL LEAKAGE TESTER

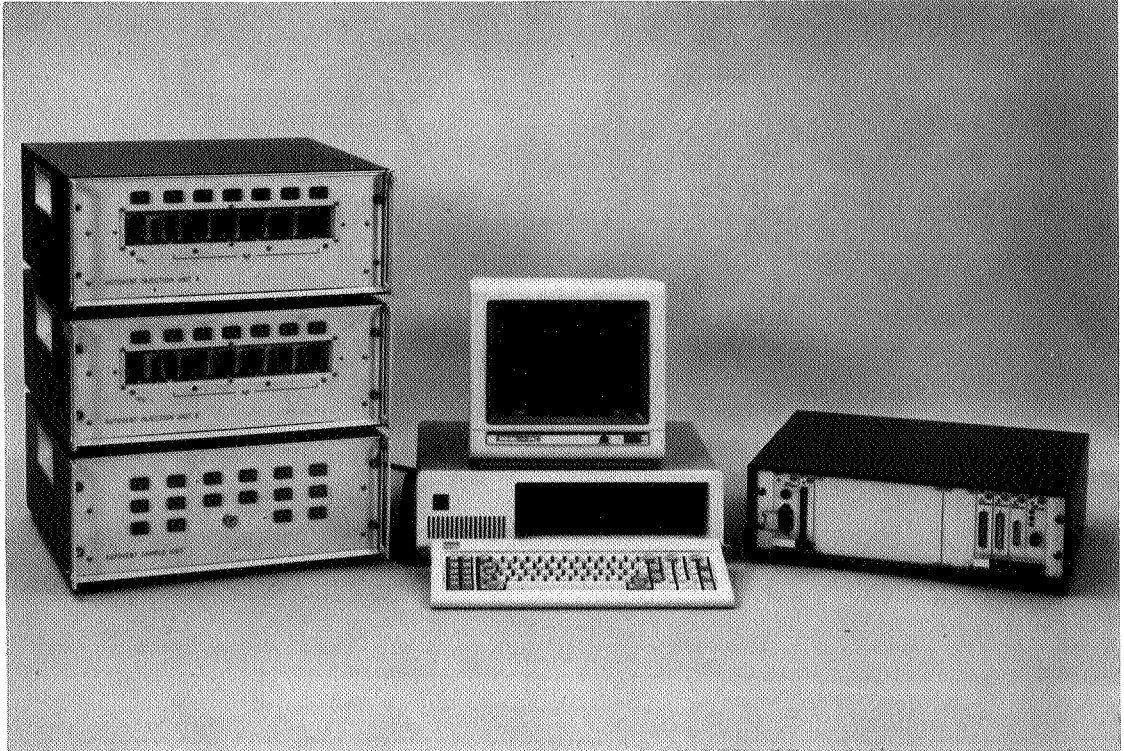


FIGURE 3 : BRITISH GAS AUTOVENT



FIGURE 4 : MOBILE VENTILATION LABORATORY

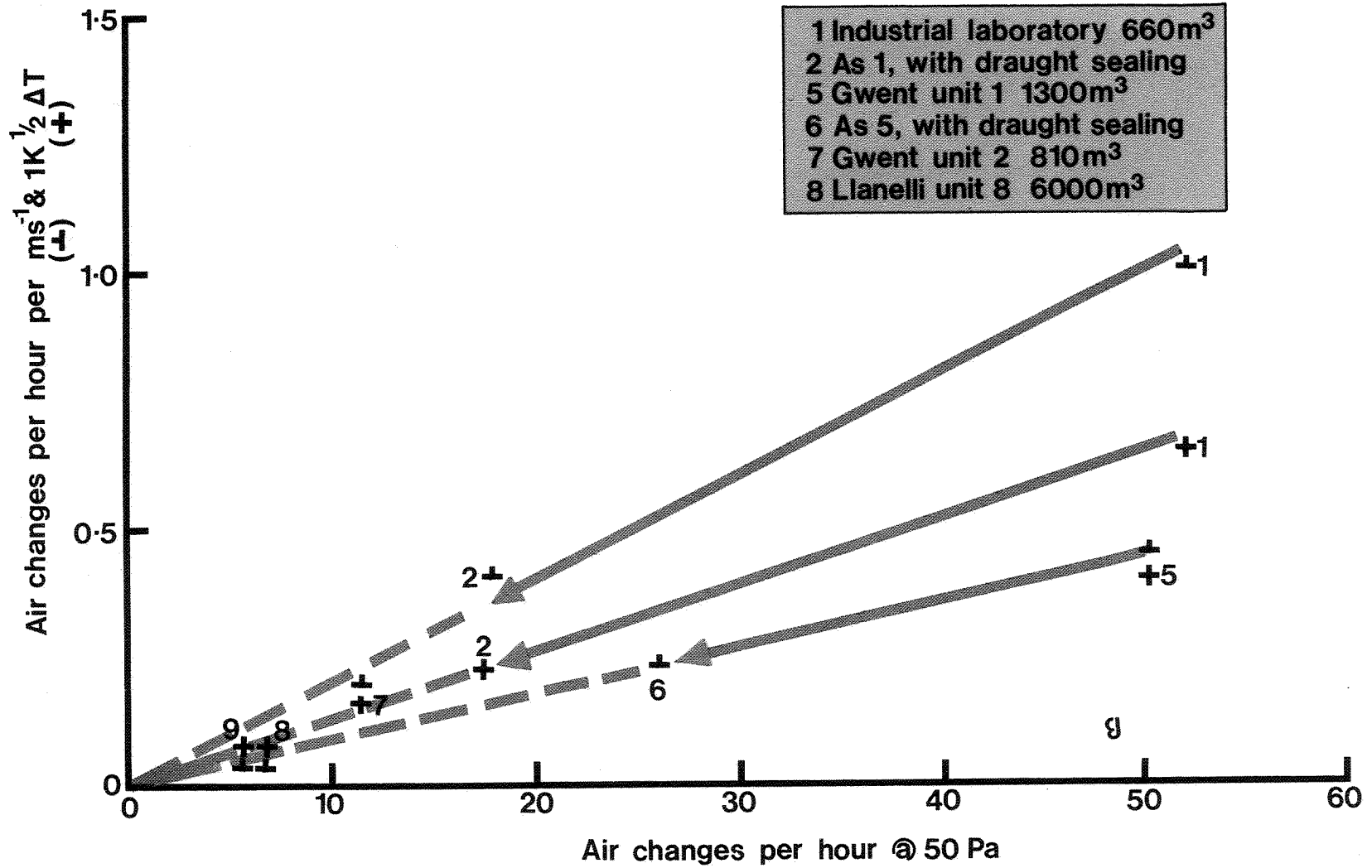


Fig.5 THE COMPARISON OF BUILDING LEAKAGE @ 50Pa ΔP AND SPECIFIC VENTILATION RATE FOR A RANGE OF LARGE BUILDINGS

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POSTER P5

THE INFLUENCE OF TEMPERATURE VARIATION ON STACK EFFECT IN
HIGH-RISE BUILDINGS

K.H. Lee¹, Y. Lee¹ and H. Tanaka²

¹Department of Mechanical Engineering
University of Ottawa, Ottawa, Canada, K1N 6N5

²Department of Civil Engineering
University of Ottawa, Ottawa, Canada, K1N 6N5

SYNOPSIS

A study has been made, both experimentally and analytically, on the characteristics of thermal performance of high-rise buildings using a simulated model building with five floors and a number of exterior openings under various temperature distributions. The effect of the temperature variation on the location of the neutral pressure level (NPL) was of particular interest of the present study. The results also show that for the prediction of thermal effect in high-rise buildings with floor partitions under a given temperature distribution, a nondimensional parameter representing the ratio of floor opening to exterior opening areas has a dominant role.

SYMBOLS

A	Area
b	Constants in Eq. (1)
D	Diameter, equivalent
f	Friction factor
g	Acceleration of gravity
H	Height of the building
K	Form loss coefficient
L	Length of the openings
P	Pressure
R	Gas constant
T	Temperature
v	Velocity
z	Height
ρ	Density

Subscripts

i	Inside
o	Outside; at $z = 0$
n	At $z = \text{NPL}$
p	Floor partition
r	Reference
w	Exterior wall
crit	Critical

1.0 INTRODUCTION

Air filtration is directly related to heat loss/gain through building enclosure or the transfer of odors, dust and other pollutants. The heat loss due to air filtration for insulated buildings of good construction in Canada is said to be from 30 to 40% of total heating requirements [1]. The safety regarding spread of fire and smoke in buildings also has significant relation to this topic [2].

The air filtration through building envelopes are influenced mainly by three factors; i.e., external wind flow, temperature difference between the inside and outside of the building and mechanical ventilation operation. The second cause is often referred to as the stack effect which has been found to be one of the two major causative factors for the pressure drop across building enclosure [3].

The profile and distribution of pressure differentials induced by thermal effect depend upon the construction, design and environment of the building such as exterior openings, floor partitions and temperature distributions. The magnitude of the stack effect in Canadian winter was found to be comparable to the wind-induced pressure at a mean speed of about 12 m/s [1] and even for one or two storey houses, its effect in winter time is known to be sufficient enough to induce significant air filtration [4].

It has been shown by both experiment and analysis [5] that the stack effect equation derived from the ideal gas equation of state for the uniform outside and inside temperature of a building is accurate for the prediction of the pressure differentials induced by the stack effect provided that the value of the neutral pressure level (NPL) is known correctly. The study also demonstrated that the existing method recommended by ASHRAE [6], applicable only for a simple case of openings at top and bottom levels with uniform outside and inside temperature, for the value of NPL is inadequate.

Reported herein are the results of an analytical and experimental study on the stack effect in a high-rise building where the internal temperature has a non-uniform distribution.

2.0 ANALYSIS

The schematic diagram of the analytical model is presented in Fig. 1. It represents a hypothetical tall building with floor partitions and external openings. The opening holes and crevices given by the elevator doors, stairways and various service shafts, etc., are first lumped together and represented by an equivalent orifice through the floor separation. The openings through the external envelope of the building, such as crevices around the windows and doors etc., are also represented by the equivalent exterior orifices. The opening areas per floor of these holes are expressed by A_p and A_w , respectively. The effect of the partitions between rooms in the same floor is not considered.

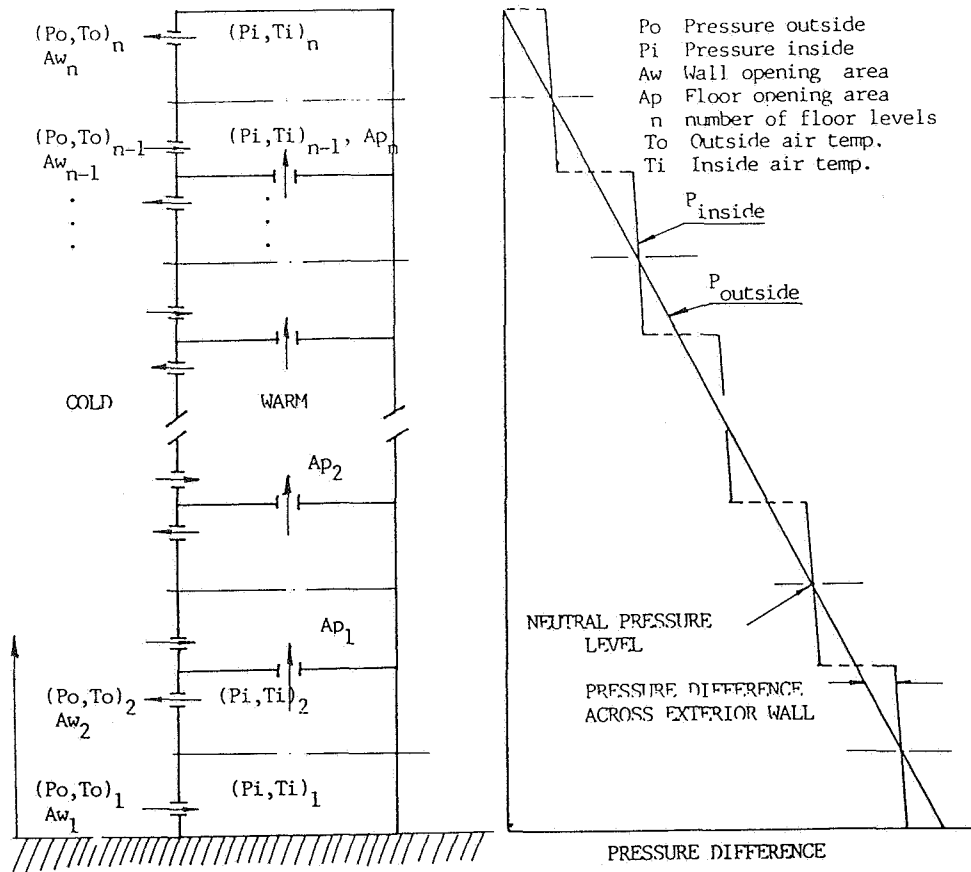


Fig. 1 Idealized Model

The major assumptions introduced for the analysis are as follows:

i. Both the inside and outside temperatures are a linear function of height as given by the following equation;

$$T_q(z) = T_q(z_r) \pm b_q z \quad (1)$$

where $q = \text{in or out}$,

ii. there exists no wind and mechanical ventilation actions on the building; and

iii. the flow field at the openings is steady, laminar and hydrodynamically smooth transition.

2.1 Pressure Distribution

The density difference of air between the inside and the outside caused by temperature differences across the exterior wall generates either a negative or positive inside pressure differential, depending on the magnitude of the two pressures and induces an airflow through the openings at a given elevation as illustrated in Fig. 1. The flow or pressure differentials induced by the density difference can be analyzed using the energy equation.

With Eq. (1), the governing differential equation for the pressure along the building is:

$$\left(\frac{dP}{P}\right)_q = \frac{gdz}{R[T_q(z_r) \pm b_q z]} \quad (2)$$

Integrating Eq. (2), the pressure difference due to the thermal effect between the inside and outside of the building at a given level in terms of the NPL, z_n , and the reference level, z_o (i.e., the bottom n level opening), is obtained as:

$$\Delta P(z) = P_o(z_n) \left\{ \left[\frac{T_o(z_o) \pm b_o z}{T_o(z_o)} \right]^{\mp \frac{g}{b_o R}} - \left[\frac{T_o(z_o) \pm b_o z_n}{T_o(z_o)} \right]^{\mp \frac{g}{b_o R}} \left[\frac{T_i(z_o) \pm b_i z}{T_i(z_o) \pm b_i z_n} \right]^{\mp \frac{g}{b_i R}} \right\} \quad (3)$$

Eq. (3) is the basic equation for the pressure differential due to thermal effect with the temperatures distributions given by Eq. (1).

The value of NPL, z_n , may be obtained from the equations of conservation of mass and energy including the resistance, both friction and form loss, written along the flow paths of the wall openings.

2.2 Energy Equations

The energy equations representing the pressure drop across the holes are expressed as follows:

For the exterior wall openings:

$$(\Delta P)_k = (P_o - P_i)_k = \pm 0.5 \rho v^2 \left(f \frac{L}{D} + \Sigma K \right)_k \quad (4)$$

where subscript k denotes the location of k-th opening, and the positive and negative signs are taken as the in-flow and out-flow openings, respectively.

For the openings at the floor partitions:

$$(\Delta P)_j = (P_i)_{j+1} - (P_i)_j = \pm 0.5 \rho v^2 \left(f \frac{L}{D} + \Sigma K \right)_j \quad (5)$$

where subscript j denotes j-th floor opening. In these equations K includes all the form loss terms such as entrance loss, exit loss and losses due to bends. The friction loss coefficient, f, depends on the shape of the orifice. For the present analysis, the openings of the experimental test section are circular orifices, which can be handled by the ordinary Darcy-Weisbach expression. The crevices in actual buildings are assumed to be of rectangular shape and the corresponding friction loss is calculated using the concepts of the equivalent diameter [7].

Once the pressure drop across each opening is formulated, the mass conservation equation for each closed space is given as:

$$\Sigma (\rho v A)_{in} = \Sigma (\rho v A)_{out} \quad (6)$$

and the equation of state for a perfect fluid make a complete package to solve the flow rate and corresponding pressure drops, ΔP , at any point across the building wall or floors.

2.3 Method of Solution

Owing to the temperature variation, the expression for the NPL is somewhat complicated and requires an iterative method.

The energy equations, Eqs. (4) and (5), corresponding to the number of exterior and interior openings in the building, are rearranged by interrelating between the openings at different levels together with Eqs. (3) and (6), and a set of equations in terms of velocities is obtained.

The total number of equations as well as the number of unknowns are identical to the number of the openings involved in the fluid flow induced by the thermal effect in the building.

Since the equations formulated include non-linear terms, the Newton's method for the solution of the set of non-linear equations [8] was used in the present study. In the method, the values for the unknowns are determined by calculating the given function with a small perturbation for each of the variables in turn, to improve the accuracy of the estimation.

The computations are initiated with assumed values for the flow velocity in the openings involved for the case under consideration. When the convergence is obtained, the next procedure to satisfy mass conservation in the system is taken.

3.0 EXPERIMENT

The purpose of the experimental program in this study is to verify the accuracy and usefulness of the analytical model described above. Therefore, the model building used in the experiment is meant not to simulate any particular building but to simulate the mechanism of stack effect in building structures. A schematic diagram of the model building simulating a high-rise building with floor partitions is presented in Fig. 2.

3.1 Description of the Test Model Building

The test section is made of 18.3 m long, vertical copper pipe with 50.8 mm ID and is equipped with 20 separate heating units along its height. Each heating unit is about 0.90 m in length and has an independent heat element which can be controlled individually. The copper pipe is thermally insulated from the ambient air. Thus, the internal temperature distribution can be given in any designed profile.

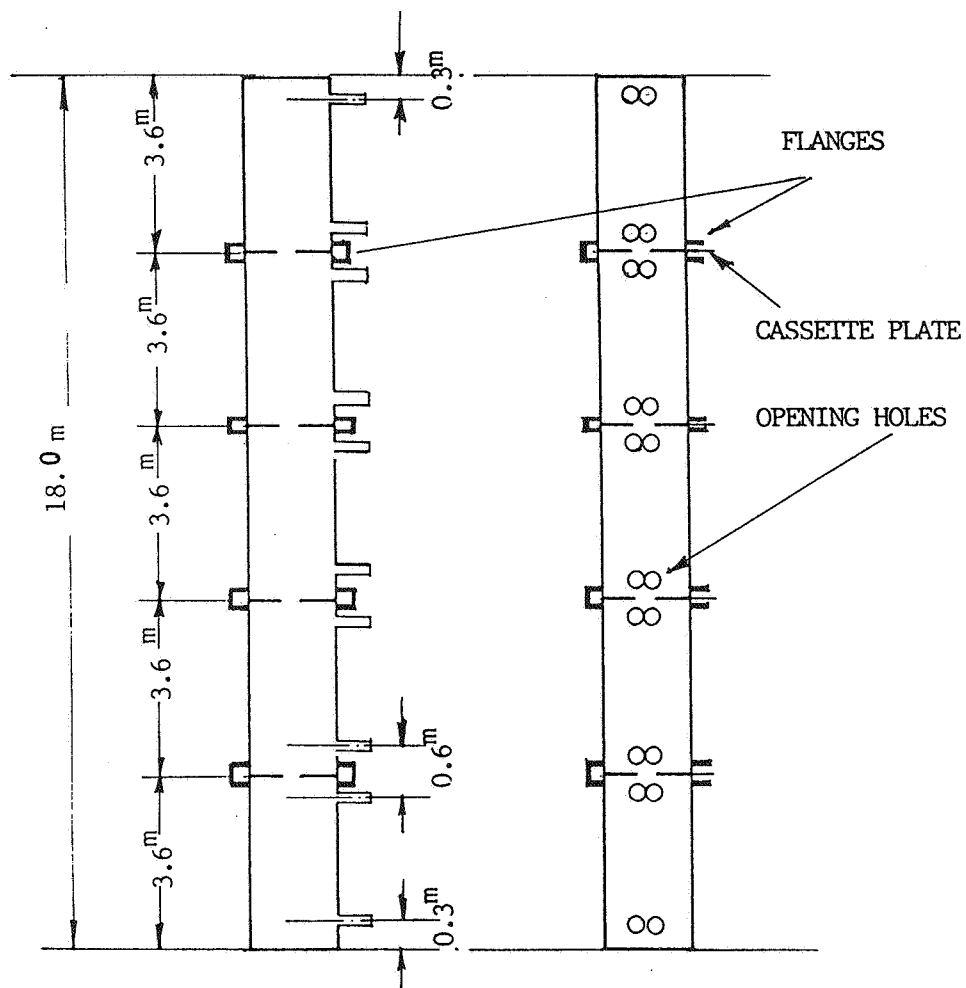


Fig. 2 Test Section with Floor Partitions

20 sets of variable transformers with 1 KW capacity, 110 V and 10 A are used to supply the power to each heating unit. The power to each heating unit is controlled by these variable transformers, and it is measured by both a digital voltmeter and an amperemeter through the measuring circuits.

38 K-type thermocouples are used in total for the measurement of temperature profiles of the test section. 20 thermocouples are spot-welded on the outer surface of the copper tube of the test section (at the center of each heating unit) to measure the wall temperatures of the test section.

In addition, 8 thermocouples were provided on the outside surface of the test section to supplement the 20 thermocouples mentioned above. 5 thermocouples, which are sheathed K-type with 152 mm long, 0.82 mm O.D stainless steel tubing, are inserted into the temperature measuring tap of the test section to measure the inside air temperature along the elevation. Another 5 were placed outside to measure the variation of the outside temperature along the test section.

Seven pressure taps were directly connected to seven sets of MKS Baratron type 220B pressure transducers with maximum pressure head of 1 torr (133 Pa), and 0.15% error at full scale. One of two pressure ports of each transducer was connected to the pressure tap of the test section and another port was connected to 17 gauge stainless steel tubes mounted immediately outside the test section at the same elevations. The signals from the pressure transducers are sent to the Data Acquisition System via a HP 3495A Scanner.

The tube is also equipped with a floor separation mechanism, which was done by inserting four cassette plates between flanges mounted on approximately every 3.6 m of the tube. The cassette plate is made of aluminum and 3.0 mm thick. The flanges are designed to allow removal and insertion of the cassette plates into flange gaps to control the air tightness of the partition as designed.

Each cassette plate has a circular hole with the diameter ranging from 1.0 to 20.0 mm at the center to simulate the porosity of the building floor separation. To simulate the external wall openings, four holes are provided for each section. Each hole is made of a copper tube of 5.0 mm ID and 75 mm long.

The height of each floor, 3.6m, is similar to the usual floor height of ordinary buildings. The cassette plate is made of aluminum and 3.0 mm thick. The flanges are designed to allow removal and insertion of the cassette plates into flange gaps to control the air tightness of the partition as designed. Each cassette plate has a circular hole at the center to simulate the crack openings of the building floor. To simulate the exterior wall openings, four holes are provided for each floor of the test section as shown in Fig. 2. Each hole is made of copper tube of 5.0 mm I.D. and 75mm long. These holes, of course, can be closed depending on the designed experimental conditions.

3.2 Data Acquisition System

The Data Acquisition System used in the present study consists of a Hewlett-Packard (HP) desk top computer with four other HP instruments as follows; HP 9835A computer, HP 3455A Digital Voltmeter, HP 3495A Scanner, HP 7245A Printer/Plotter and HP98305 Real Time Clock. The raw and reduced data are stored on magnetic tapes. Hard copies were also made available.

3.3 Experimental Procedures

The simulation of thermal effect is carried out through careful and cautious adjustment of power supply to each heating unit with continuous measurements of current and voltages supplied and the temperature distribution along the test section. This procedure is continued until the desired temperature distribution is achieved with the maximum allowable wall temperature deviation of 2 to 3 C at each point. The range of temperature difference across the wall of test section in this study is between 30 and 90 C.

4.0 RESULTS AND DISCUSSIONS

A series of experiments was carried out to confirm the validity of the above mentioned analytical model. The number of floors and the size of floor openings were varied by removing/inserting or replacing the cassette plates described in the preceding section. Since the outside air temperature was difficult to control in the experimental studies, the cases of non-uniform inside air temperatures with a uniform outside air temperature only were experimentally studied. The two linear temperature distributions used in the experiment are:

$$T(z) = 30.0 + 3.3z \quad (7)$$

$$T(z) = 90.0 - 3.3z \quad (8)$$

4.1 Thermal Effect in Building without Floor Partitions

Example of the experimental results on the thermal effect in building without floor partitions using the inside air temperature distribution represented by Eq. (7) are shown in Fig. 3 while the results obtained using those given by Eq. (8) are illustrated in Fig. 4, for various cases of external wall openings.

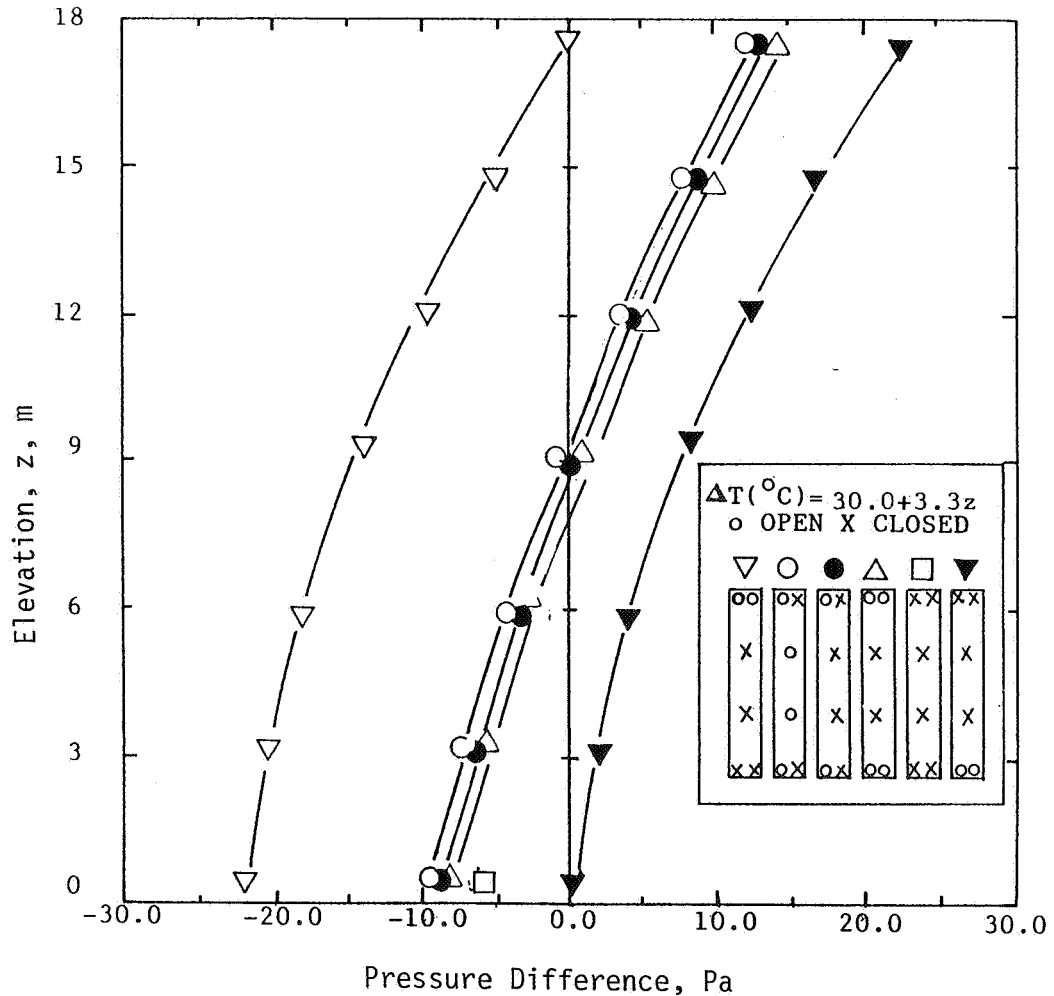


Fig. 3 Experimental Results

Figs. 5 and 6 demonstrate a comparison between the predicted and measured values. The agreement between the experiment and analysis is excellent. The results show that the location of NPL and the curvature of the pressure distribution along the height of the building are affected by the temperature distribution.

The coefficient of temperature gradient, b , is seen in Fig. 7 to have rather strong effect on the slope but very little on the location of NPL. The pressure differential across the exterior wall increases with increasing value of " b ".

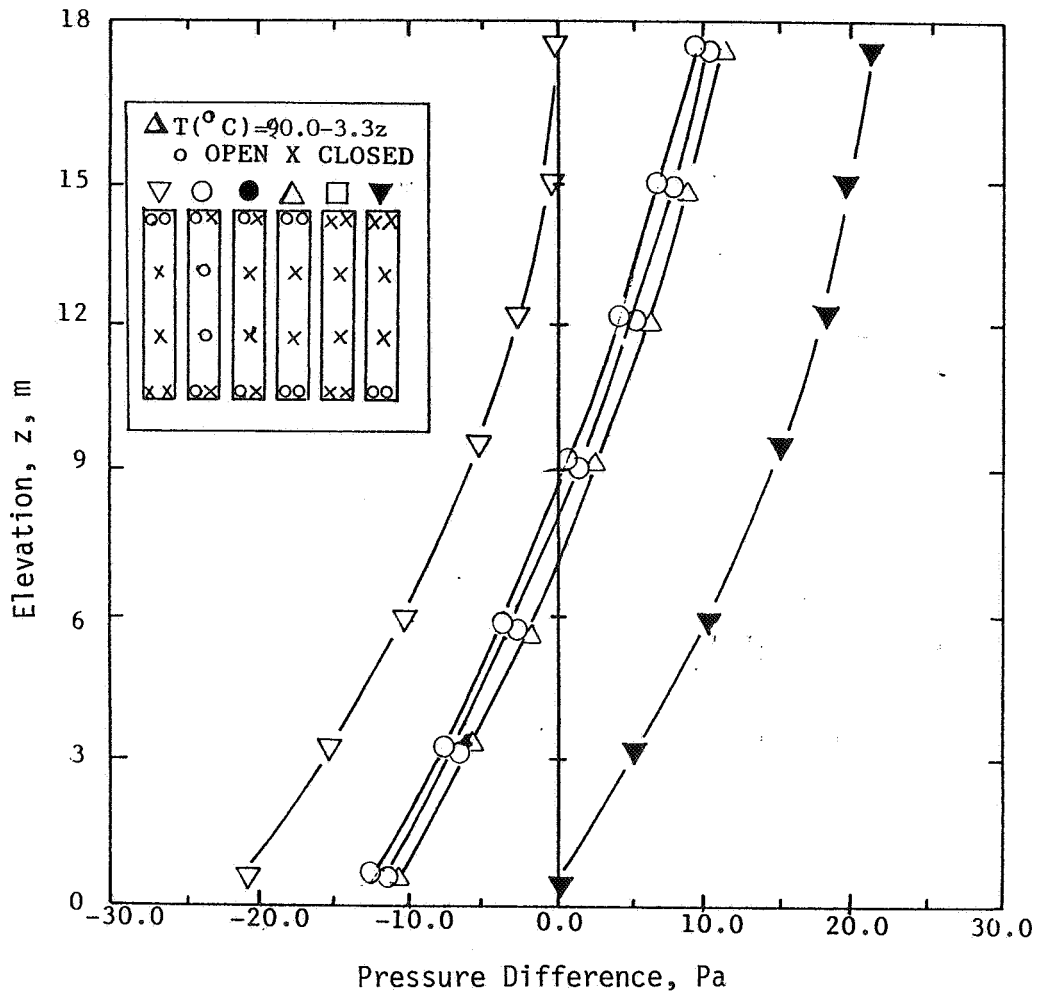


Fig. 4 Experimental Results

Fig. 8 illustrates the results of analysis on the effect of " b " with respect to the location of NPL for various cases of exterior wall openings. In all cases, the values of NPL appear to increase slightly initially as the value of " b " increases, but it becomes almost asymptotic to a constant value for $b > 0.8^{\circ}\text{C}/\text{m}$. The asymptotic values of NPL shown in Fig. 8 are about 4% higher than those obtained from the cases where the inside air temperatures were kept uniform.

4.2 Thermal Effect in Building with Floor Partitions

4.2.1 Effect of Floor Opening

Typical experimental results are shown in Fig. 9. In the figures, the vertical profiles of the pressure differentials across the building envelope are plotted for three different values of the area ratio parameter, Ap^* . This parameter is defined by the ratio of the opening area in the floor partition to that of the external wall; i.e., $Ap^* = Ap/Aw$, so that the relative magnitude of the resistance to flow imposed by the floor separations can be evaluated. The thermal boundary condition for Fig. 9 was the same as that shown in Fig. 3.

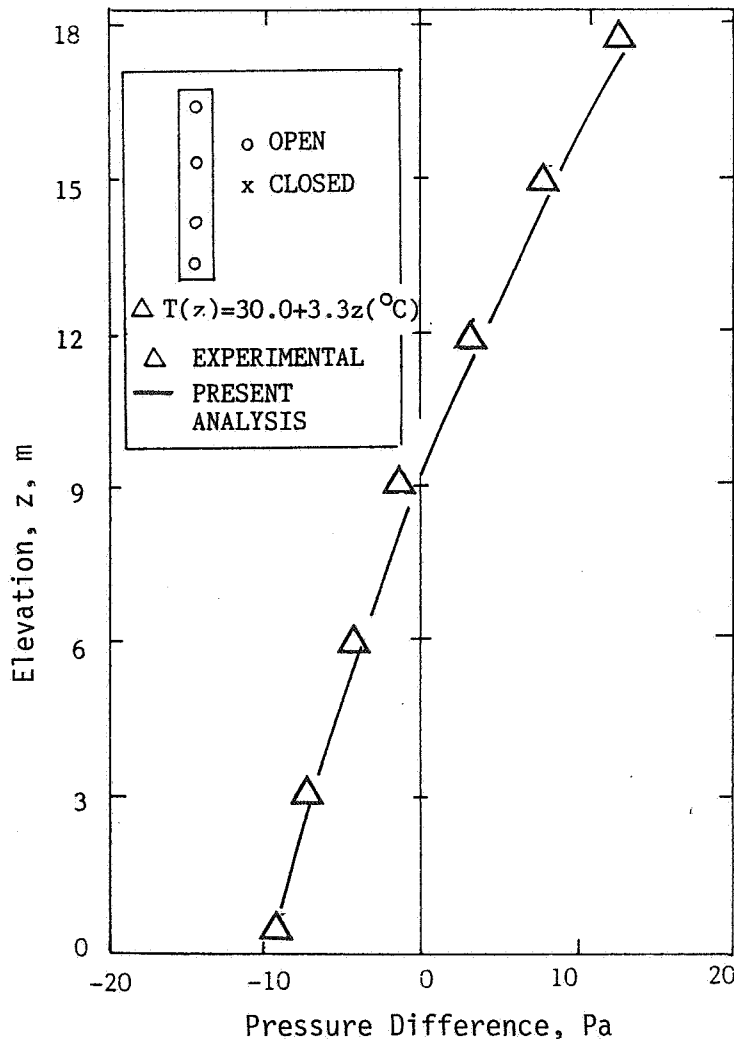


Fig. 5 Comparison of Analysis vs. Experiment

It is evident that the agreement between the present analysis and the experiment is excellent in the range of the area ratio Ap^* studied.

As seen in the figure, the pressure difference across floor separations decreases with increasing values of Ap^* . Once it exceeds a certain value, the pressure curve along the height of the building becomes almost linear as if there were no floor partitions at all. For the cases shown in Fig. 9, the critical value of Ap^* was about 8.

Also presented in the figures are the analytical results obtained from the computer model for the cases under the

For a very small value of Ap^* , as it would be expected, the pressure difference across floor partition increases significantly with the increased resistance to air flow at the openings. Correspondingly, the thermal effect in each floor appears to be less affected by other floors. Hence, it may be concluded that for the prediction of the thermal effect, it is essential to know the relative magnitude of flow resistance at the floor partitions.

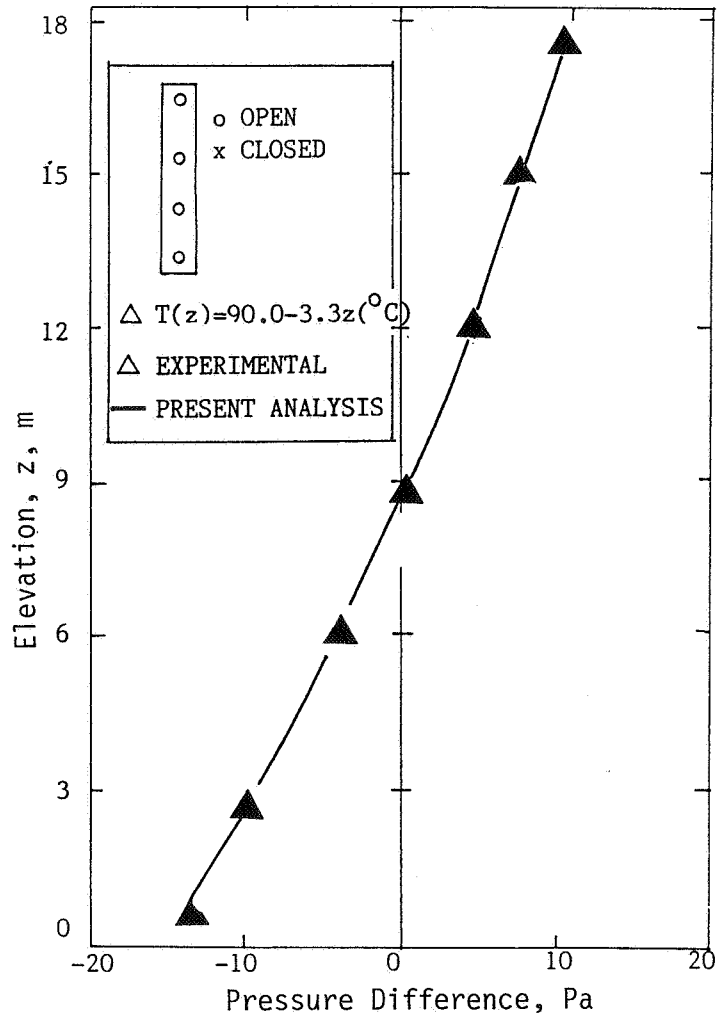


Fig. 6 Comparison of Analysis vs. Experiment

4.2.2 Critical Value of Ap^*

As is obvious from Fig. 9, when the area ratio Ap^* is larger than a certain value, the effect of floor separation is practically non-existent as far as the stack effect is concerned. In order to make this point clearer, the concept of the critical value of Ap^* was introduced as follows [9]:

When $Ap^* > (Ap^*)_{crit}$, the magnitude of the pressure drop across floor partition, $(\Delta P)_p$, is less than 1% of $(\Delta P)_{p,max}$, where $(\Delta P)_{p,max}$ is the magnitude of $(\Delta P)_p$, at $Ap^* = 0$; i.e., the case of perfectly air-tight partition.

Fig.10 represents the calculated values of $(Ap^*)_{crit}$ defined above at a multi-story building with various

patterns of wall openings under both uniform and non-uniform inside air temperature conditions. The results for some configurations for the non-uniform inside air temperature distributions are also supported by experimental results.

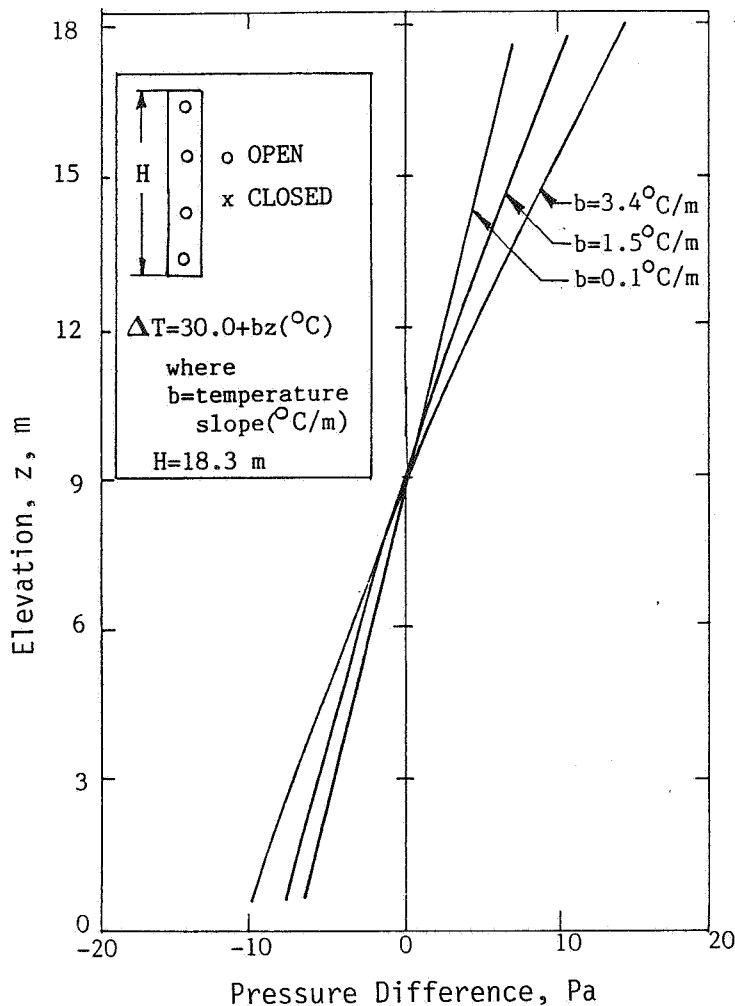


Fig. 7 Effect of "b" on Pressure Distribution

As shown in the figure, critical Ap^* varies depending on the distribution of the exterior wall openings, but is found to be approximately in the range of 10 to 15 for the case of tall buildings. This is an interesting result because if the area of wall opening per each floor is typically the order of 10^{-4} m^2 for a tall building, for example, the critical value of Ap for the same building is approximately 10^{-3} m^2 per floor, which is a very much smaller value than would be expected from

the door cracks of elevator shafts, stairway and various other service shafts in average construction.

Fig. 10 also illustrates that the critical value of $(Ap^*)_{\text{crit}}$ obtained from this case appears to be nearly the same as that of the partitioned building with uniform temperature distributions. From these results, it can be deduced that the effect of the non-uniform distributions of inside air is shown to be insignificant on the critical value of $(Ap^*)_{\text{crit}}$.

Fig. 11 represents the effect of the temperature slope of the inside air, b , on the pressure differential profile due to the thermal effect for the different

exterior opening patterns for buildings with four floor partitions. In the analysis, the ratio of floor opening to the exterior wall opening at each floor, (Ap^*) , is made to be greater than $(Ap^*)_{crit}$ in all the cases. The effect is similar to those already shown in Fig. 7 for the case of no floor partitions under non-uniform temperature distributions.

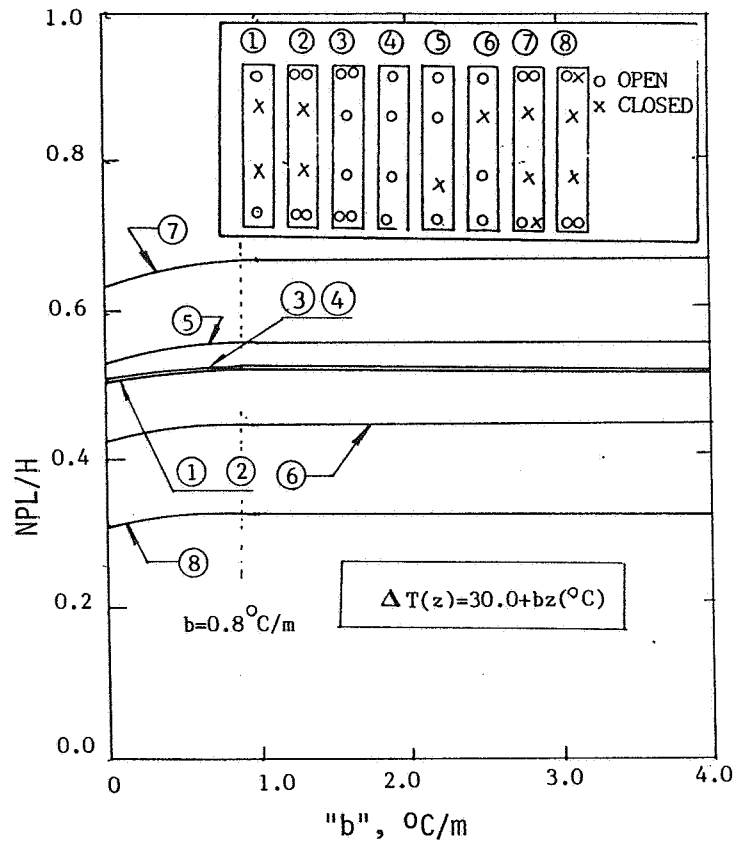


Fig. 8 Effect of "b" of Inside Air on NPL

4.2.3 Location of NPL

As was stated above, once the area ratio (Ap^*) exceeds the critical value, $(Ap^*)_{crit}$, the behavior of thermally induced pressure differential becomes the same as that of the open shaft buildings without any internal compartmentalization. Consequently, the location of NPL becomes irrelevant to (Ap^*) and is decided only by the external wall opening configuration.

The results on the effect of the temperature slope of the inside air, b , on the NPL for various distributed exterior openings are illustrated in Fig. 12. The effect is seen to be negligible as were the cases with no floor partitions shown already in Fig. 9. The values of NPL over $b = 0.8 \text{ C/m}$ are shown to be approximately 4% higher than that of the case having floor partitions with uniform temperature distribution. In practice, the effect of non-uniform temperature distributions of inside air on the neutral pressure level is marginal.

4.2.4 Effect of Both Non-Uniform Temperature Distributions of Inside and Outside Air

We have so far shown only the effects of the non-uniform temperature distributions of inside air along the height of buildings with a uniform outside air temperature, on the pressure differential profiles induced by thermal effect.

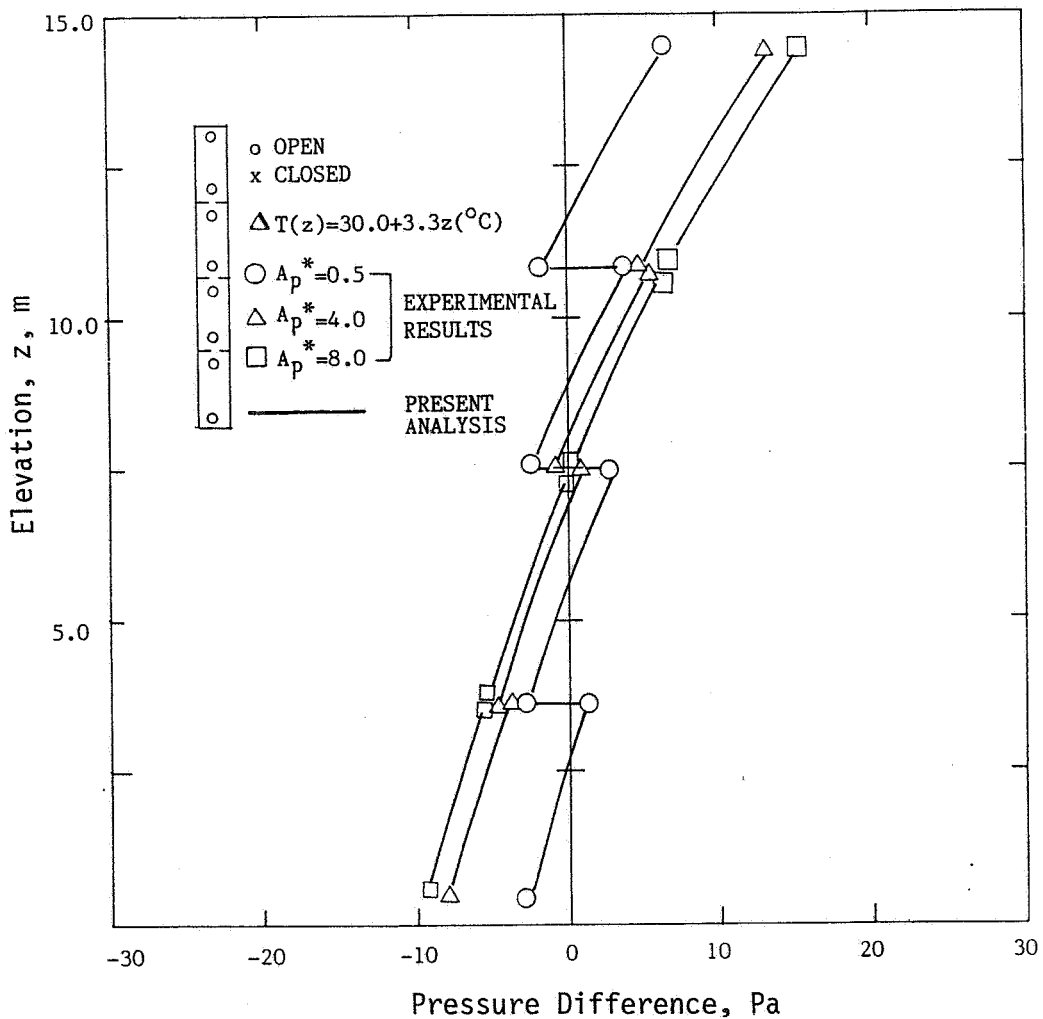


Fig. 9 Effect of A_p^* on Pressure Distribution

In reality, it is quite possible that both the inside and outside air temperatures may vary along the height of buildings. Fig. 13 represents the analytical results for the case with floor partitions, in which (A_p^*) is greater than $(A_p^*)_{crit}$. Four different temperature difference distributions along the building height are studied as shown in the figure.

It can be seen that the case of Type I which has a non-uniform temperature distributions of inside air only, is shown to have higher value of NPL/H than others.

Conversely, the case of Type IV has appeared to give lower NPL/H than others. The maximum difference between the highest and the lowest value of the NPL/H is shown to be less than 5% for the cases shown in the figure. Similar trends are also observed in other cases where exterior wall opening patterns were quite different.

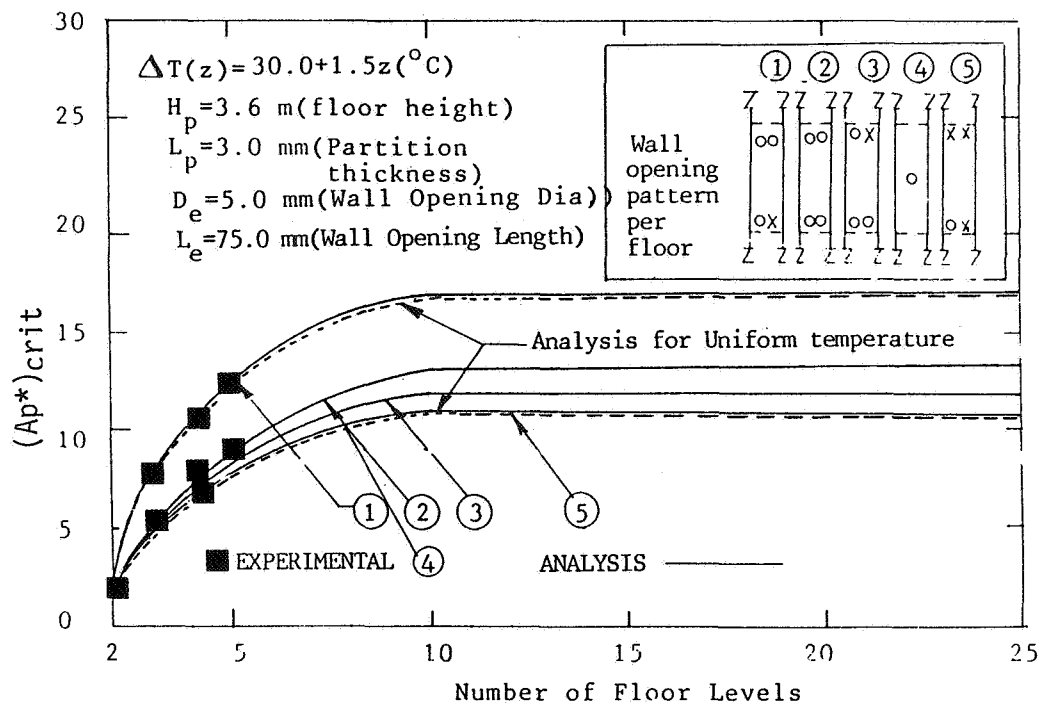


Fig. 10 Effect of Number of Floors on $(A_p^*)_{crit}$

From these results, we may conclude that the pressure differential profiles induced by the thermal effect in a building with floor separations is mainly governed by the distributed mode of the exterior wall openings as well as the openings in the floor separations including the number of floors even under the effect of the non-uniform temperature distributions of inside air along the building height.

4.3 Other Aspects of the Problem

Thus far, the floor openings and wall openings are assumed to have a shape of a simple orifice hole. Of course in reality, the cracks and crevices would have more complicated cross-sections and path shapes. Moreover, the number of holes may also have some effects on the results. These points are carefully examined here.

4.3.1 Problem of Orifice Shape

The effect of the crack opening configuration was analytically examined. The results showed that the effect of the geometrical shape of openings is not significant as was the case with a uniform temperature distribution of the inside air [9]. It can be concluded, therefore, that for the analysis of the thermal effect in buildings, the use of circular orifices with an equivalent diameter is probably a good representative of various types of cracks in actual buildings, provided that the equivalent diameter is properly decided.

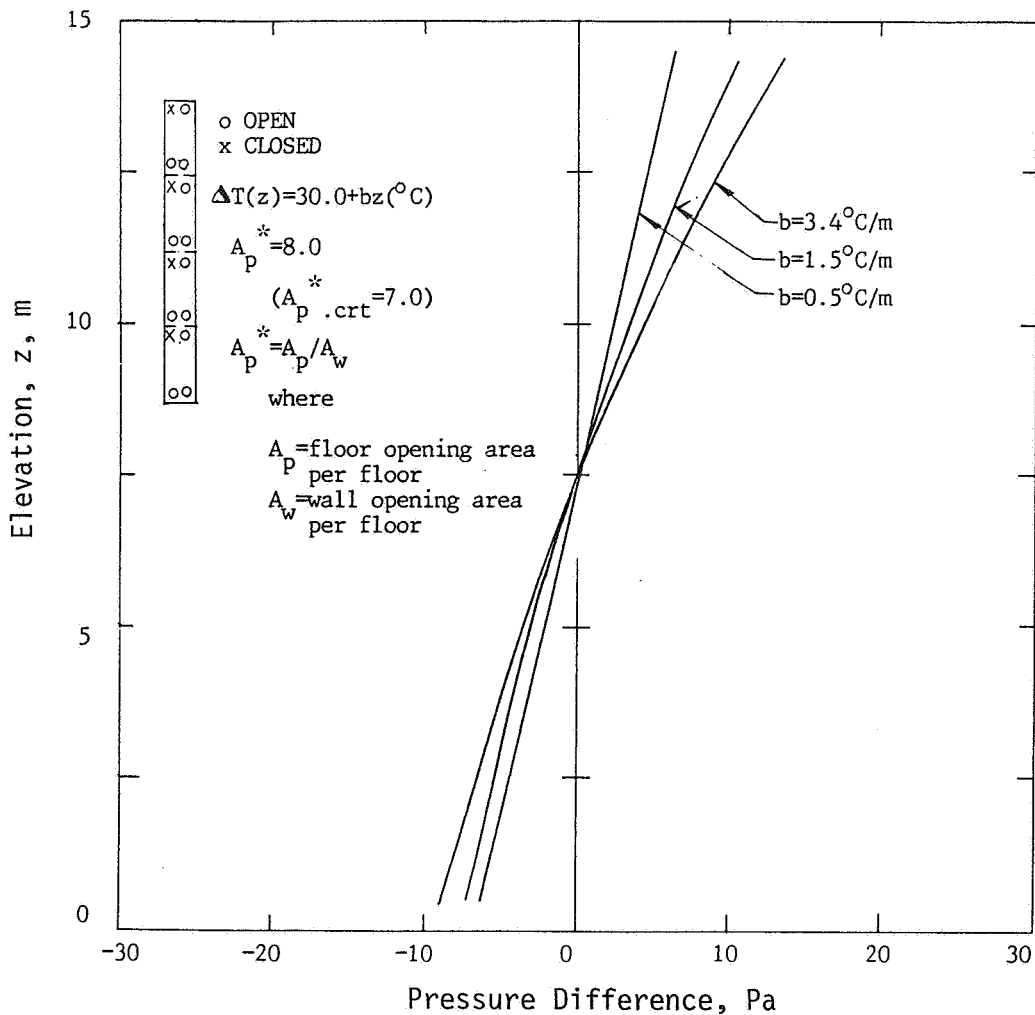


Fig. 11 Effect of "b" on Pressure Distribution; Four Floors

4.3.2 Number of Floor Openings per Floor

In actual buildings, the crack openings in the floor separations such as the cracks around elevator doors and doors to the stairways, etc., are neither situated in one place nor existing as one hole. However, in the present analysis, only one hole at the center of each floor is assumed. The possible effect of this deviation on the results should be also considered.

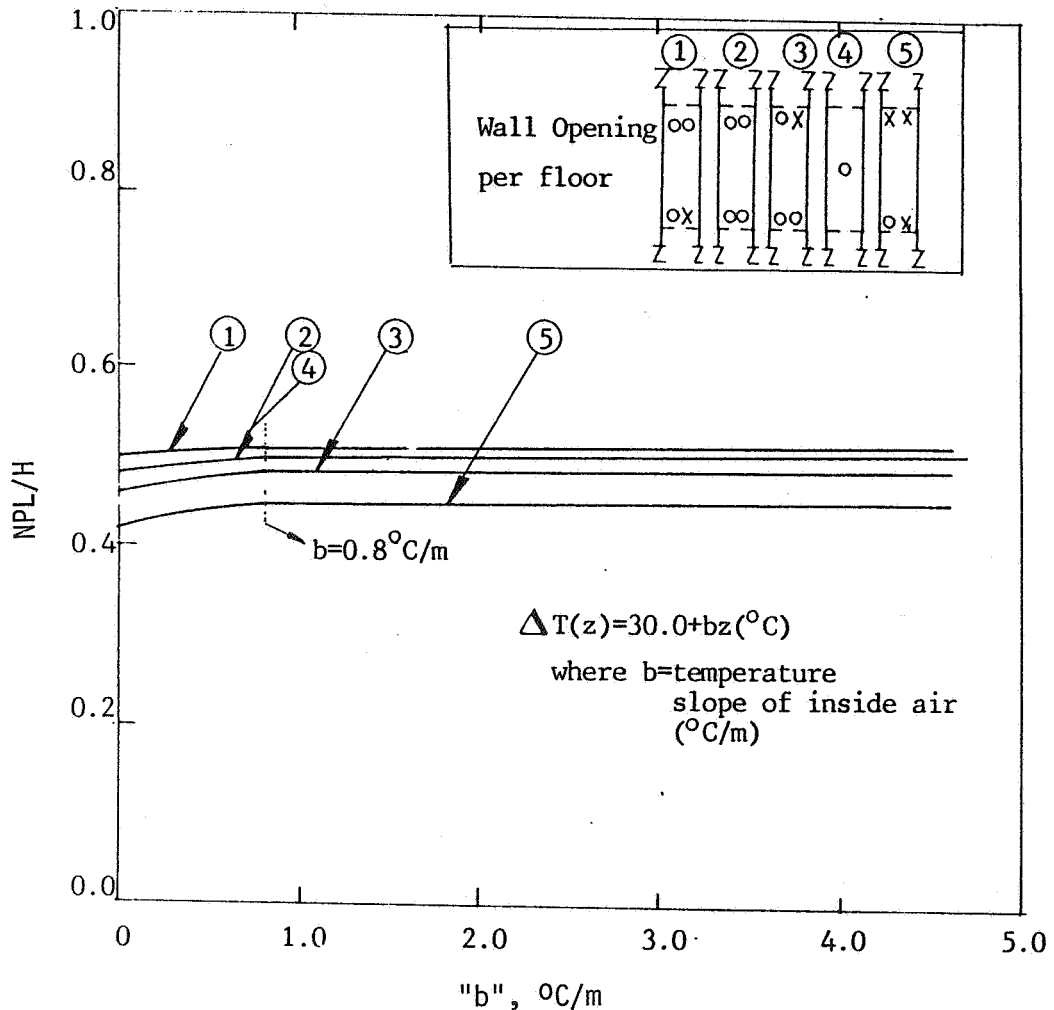


Fig. 12 Effect of "b" on NPL; Buildings with Floor Partitions

The analytical studies on the effect of dividing the floor opening area into multi-holes on the value of $(A_p^*)_{crit}$ for the cases of two floor and four floor buildings were made. The number of floor openings per floor partition, which was assumed to have the same geometrical shape and dimension, was varied from 1 to 25, maintaining the total area constant. There was a slight increase of $(A_p^*)_{crit}$ with the increase of the number of holes and this can be attributed to the

increase of flow resistance at the holes. The results suggest that by replacing multi-openings by a single hole, $(A_p^*)_{crit}$ tends to be underestimated. Nevertheless, for most of the cases studied here, the calculated critical A_p^* is less than the actual A_p^* employed in the analysis and hence the anticipated effect on the pressure calculation should not be significant.

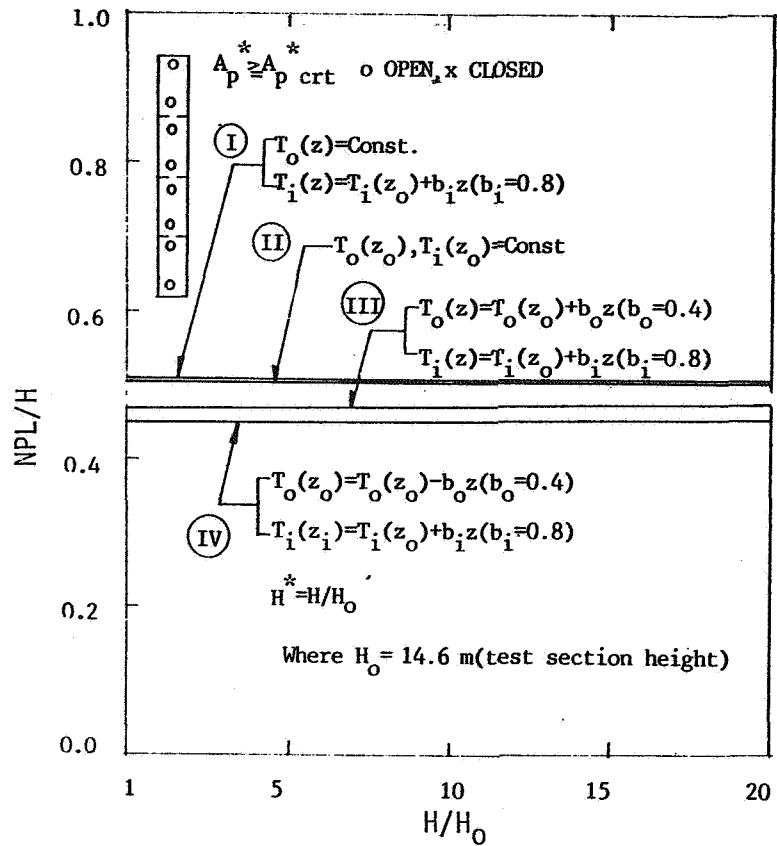


Fig. 13 Effects of "b_i" and "b₀" on NPL

5.0 CONCLUDING REMARKS

Based on the results presented above, we may conclude that the effects of non-uniform temperature distributions of inside and/or outside air along the height of buildings on the value of NPL within practical ranges of temperature differences, and on the profiles of pressure differential due to thermal effect in the actual building environment are seen to be marginal.

ACKNOWLEDGMENTS

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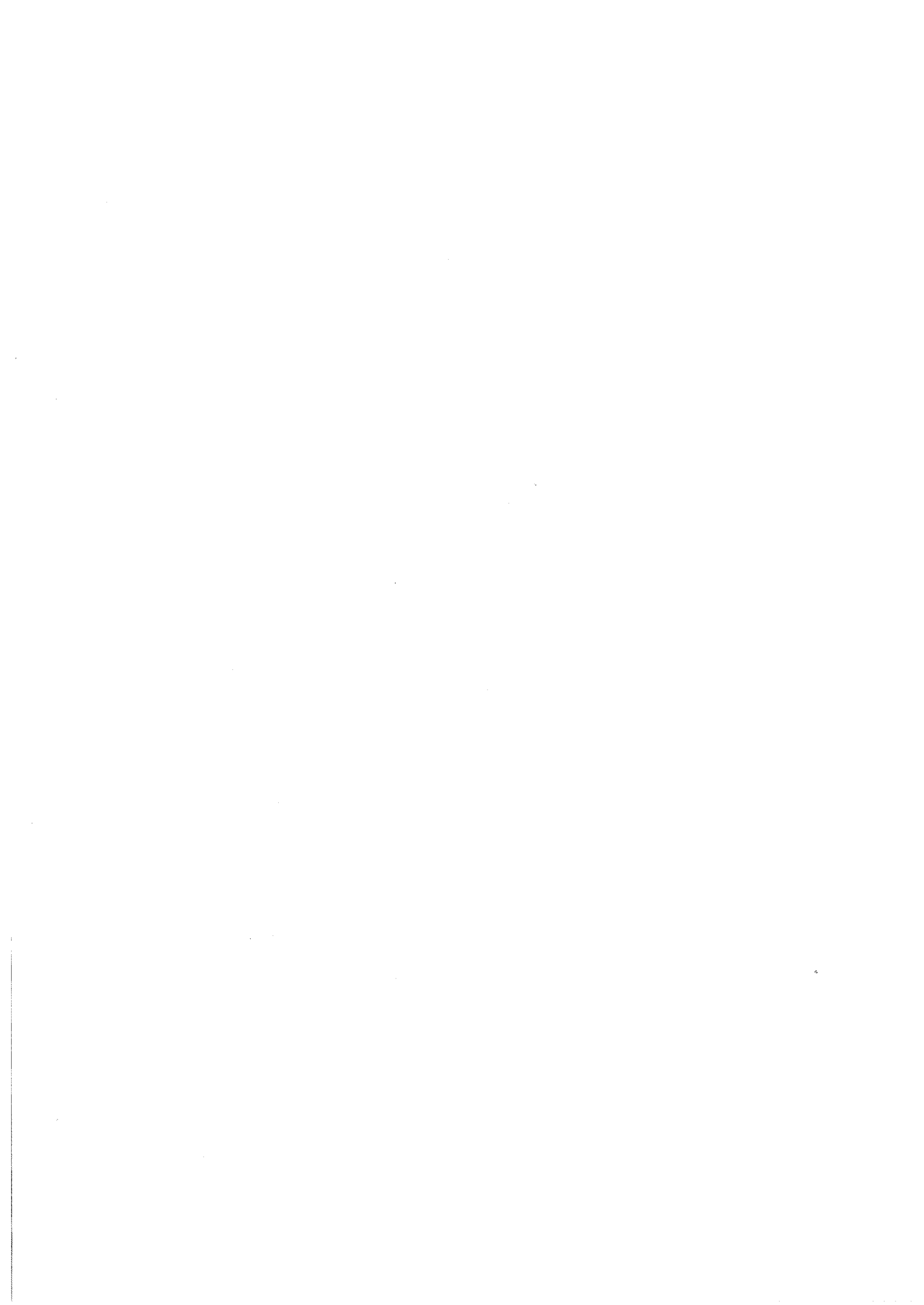
8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER P6

DISPLACEMENT VENTILATION

TOMAS HÖRZ, PER-OLOV DANIELSSON

AB Bahco Ventilation
Fack
19981 Enköping
Sweden



DISPLACEMENT VENTILATION

The mixing system (even called the dilution system) is normally used throughout the world to supply air to a premises.

In the mixing system you blow air at high velocity into the room at a temperature which gives you the wanted room temperature. If the system works perfectly, you will have the same temperature and concentration of contamination in the whole room. That is because the supplied air and the air in the room is mixed due to induction.

Mixing system

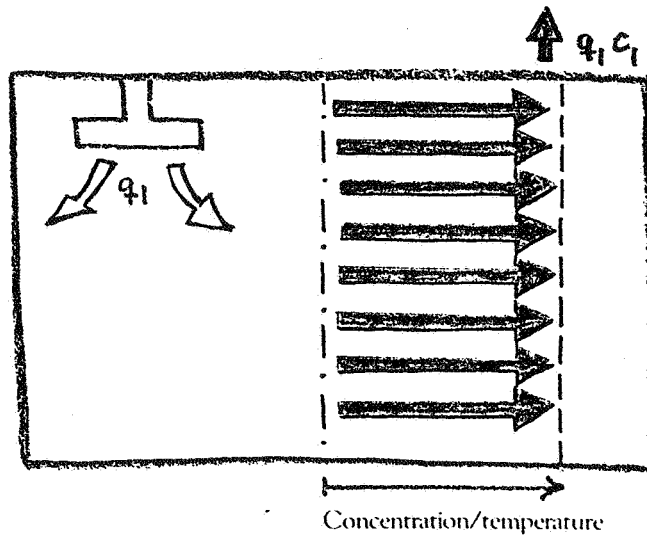


Figure 1

In Scandinavia the displacement ventilation system has had a break-through during the last years.

In this system the air is supplied through terminals with low velocity (0.2 - 0.6 m/s), which gives almost laminar flow. This together with the fact that the supplied air is slightly cooler than the air in the room gives a temperature gradient, which makes the supplied air flow out over the floor exactly in the same way as water would. The contaminated air in the room is therefore displaced towards the ceiling, where it is extracted. Warm convective air flow from different heat sources raises towards the ceiling by itself and is allowed to do this without disturbing air movements. Because of this the occupied zone is

characterized to a very high degree by the supplied air rather than by a mixture of polluted and supplied air.

Floormaster system

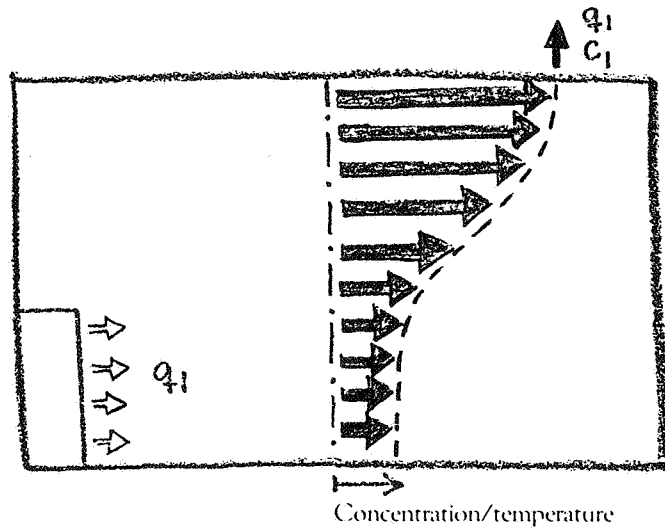


Figure 2

Let us compare a room with a given supply air flow and contamination emission. With a displacement system we will get a rather low concentration of contamination in the occupied zone and a higher concentration in the upper zone. The mixing system, however, will give this higher concentration in the whole room volume. The discussion above is valid for stationary conditions.

Result of measurements carried out in a room served by the Floor-master system.

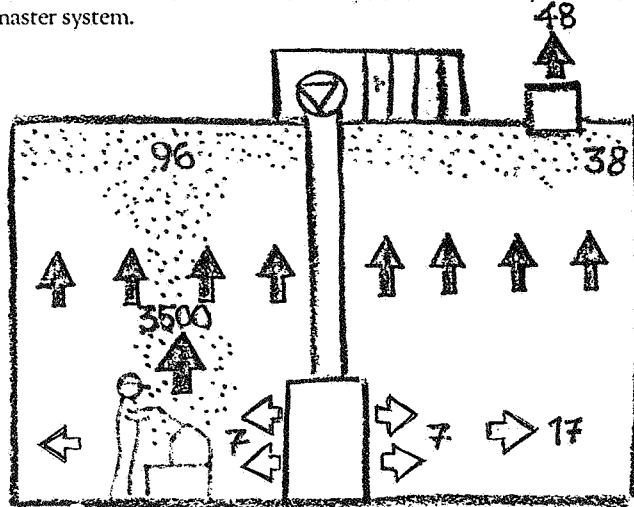


Figure 3

Figure 3 shows the result of an actual measurement in a welding workshop. The relative concentration is 48 in the exhaust air and only 17 in the occupied zone. The supply air has 7 in itself. In the same plant with a mixing system the result would be 48 in the whole room, figure 4.

Theoretical comparison with a mixing system.

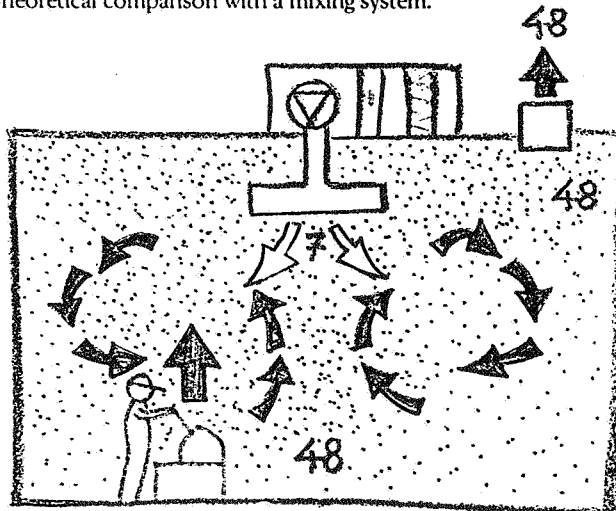


Figure 4

An adequate definition of ventilation efficiency is

$$\xi = \frac{C_e - C_s}{C_o - C_s}$$

where

ξ = stationary ventilation efficiency

C_e = concentration in the exhaust air

C_s = concentration (if any) in the supply air

C_o = mean concentration in the occupied zone.

The result for mixing system is a ventilation efficiency of 1. The result for the displacement system is 4.1 using the figures in fig. 3. This means that you would need 4.1 times more air with the mixing system to achieve 17 ppm in the occupied zone. Just think about the installation costs!

The reason for two systems to give such different results is that in the mixing system a particle in the room is recirculated several times to the occupied zone before it is exhausted. In the displacement system it rises towards the ceiling and is prevented from returning because of the thermal forces provided by the system.

In principle the temperatures in a room with a displacement system are as shown in fig. 5.

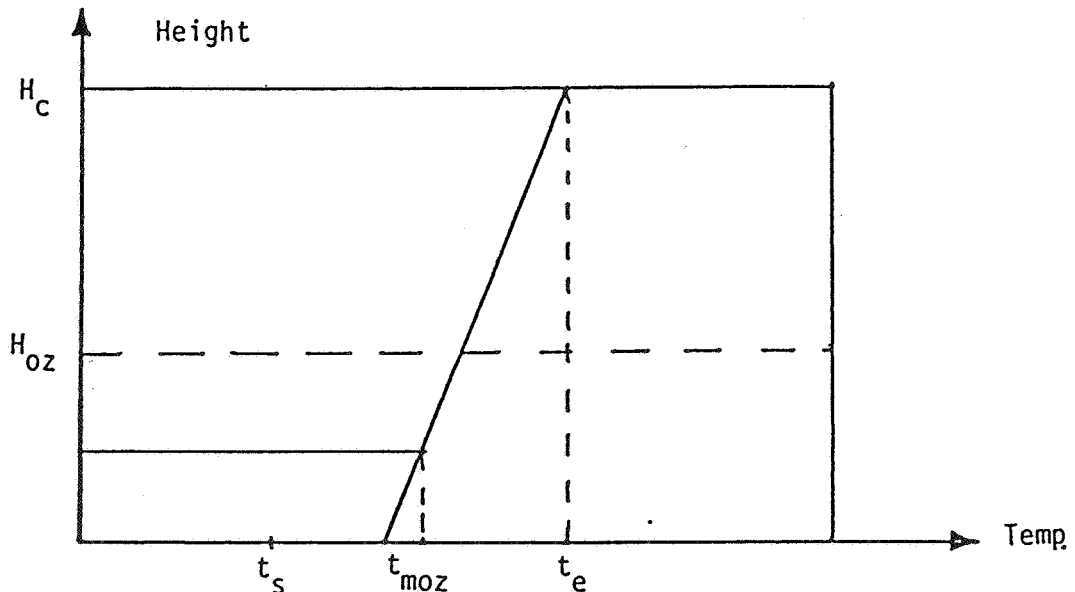


Fig. 5. Temperature profile of a displacement system.
(In reality the profile is not always a straight line.)

Explanations to fig. 5.

H_c = height to the ceiling

H_{oz} = height of the occupied zone

t_s = supply air temperature

t_{moz} = mean temperature in the occupied zone

t_e = exhaust air temperature = temperature at the ceiling.

The surplus heat in the room is taken care of by a certain supply air flow and temperature difference between exhaust air and supply air ($t_e - t_s$). In this case there is no difference between a mixing system and a displacement system. Both systems get the same value of ($t_e - t_s$) provided that the air flow and surplus heat are the same.

What differs between the systems though is the supply air temperature (t_s) needed to get the same temperature in the occupied zone. This is illustrated in figure 6.

A well functioning mixing system has the same temperature from floor to ceiling (at least almost so) and also the same exhaust air temperature. A typical example is shown in fig. 6.

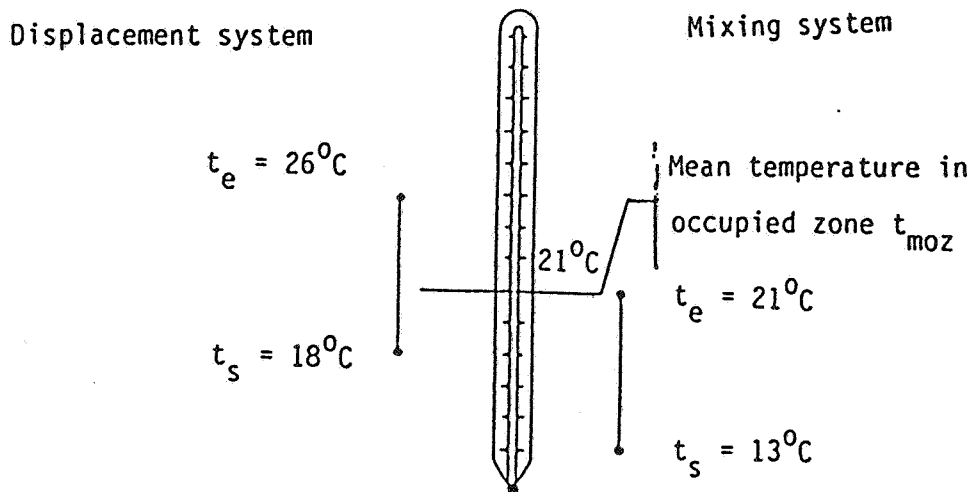


Fig. 6. Example of normal supply air and exhaust air temperatures for displacement system and mixing system.

The example shows that a mixing system demands a supply air temperature of 13°C , while the displacement system needs 18°C to achieve a suitable temperature in the occupied zone. This means, of course, that a displacement system needs less cooling during the warm season.

Another way to put it is that the displacement system gives a comfortable temperature in the occupied zone during a longer time in a plant without cooling.

The air movements, created by the two systems mentioned above are quite different. If we supply $1\ 000\ \text{m}^3/\text{h}$ at $10\ \text{m/s}$ in a mixing system, the result will be an air movement in the room of $50\ 000\ \text{m}^3/\text{h}$ at a velocity of $0.2\ \text{m/s}$. For the displacement system the corresponding value is only $2\ 000\ \text{m}^3/\text{h}$. This gives a much lower air movement which allows the temperature gradient we want to develop. It also eliminates a lot of the traditional draught problems.

One often hears that exhaust hoods do not work very well. The reason for this is often that the convective airflow from a stove is disturbed by the air movements created by the mixing system. This means that a lot of the fume will pass outside the hood.

With a displacement system the air movements are restricted to a minimum. The flow from the stove goes directly into the hood. This will create a good environment in institutional kitchens which is difficult to match.

In traditional mixing systems it is common to use recirculated air.

As the task for the outdoor air is to assure air quality, the task for the recirculating air is to provide heating, cooling and air movements when the outdoor airflow is not big enough. The reason for the need is closely connected with the demands of the existing technique e.g. the mixing system itself.

The inlet diffusors need a certain airflow to work correctly. If the flow is reduced, the undertempered supply air will not mix and therefore create draught. Consequently, by using recirculating air you can meet varying demands without changing the airflow.

Changing the flow is no problem in the displacement system. If you decrease the airflow due to decreasing demands, the system works equally well. From the systems' point of view there is no lower limit as to

how far the flow can be reduced. As the supplied air is distributed over to the floor due to its weight and not due to velocity, the whole room will be ventilated.

As a result when designing a displacement system, you will discover that the need to use recirculated air is virtually non-existing.

The criteria that speak for displacement system are:

Need of ventilation

Modern, that is well insulated, tight buildings

Surplus heat and limits for pollution

With the displacement system you can not cover transmission losses. This is virtually the only system limitation. On the other hand the system gives

- * a high ventilation efficiency
- * a high temperature efficiency that gives superior cooling capacity
- * no draught
- * it ventilates the whole room
- * it is very flexible and normally reduces ducting.

In short, with displacement system you will get better ventilation at the same price and often even cheaper.

Displacement systems are installed in a lot of different premises from tough foundries, welding shops and laundries over department stores and sport halls to concert halls, conference rooms, offices, ward rooms and operating theatres.

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POSTER P7

AIRTIGHTNESS OF MASONRY WALLS

JAN G.N. LECOMPTE

Grant Holder of The Institute for the Encouragement
of Scientific Research in Industry and Agriculture

Laboratory of Building Physics
Katholieke Universiteit Leuven
Kasteel van Arenberg
B 3030 Heverlee
Belgium



SYNOPSIS

This paper presents results of air leakage measurements on brick walls and concrete block walls, used as outer or inner leaf of a cavity wall. The results are obtained using a pressure box on a series of test walls.

The variable parameters that are examined :

- workmanship
- pointing of the joints
- plastering of the inner leaf

Out of the results can be concluded that, in general, only a plastered wall can guarantee a sufficient airtightness.

More information about this research can be found in [ref. 5], [ref. 6].

LIST OF SYMBOLS

q	(m ³ /m ² s)	air flow
Δp	(Pa)	pressure difference
a, b		coefficients in the function $q = a \cdot \Delta p^b$
ρ	(kg/m ³)	density
A	(m ²)	area

INTRODUCTION

Requirements must be formulated concerning the airtightness of masonry walls, since, next to complaints concerning comfort and an important increase of heating costs, a lack of airtightness can also cause rain penetration. In case of driving rain, windgusts can actually 'pump' a considerable amount of rainwater through the wall.

To evaluate the airtightness, measured values found in literature are however often not useful :

- the reliability is insufficient (the measurement equipment is not mentioned, few measurements,...) ;
- the airtightness is considered as constant, while in reality there is, according to the material, a more or lesser dependence on the pressure difference ;
- joints are not taken into account (e.g. the airtightness of a masonry wall is not equal to the airtightness of the brick itself) ;
- too high pressure differences are considered, while for use in applications in infiltration research and building physics, especially the lower pressure differences (0 - 20 Pa) are important ;
- workmanship, local practice and material properties can differ between regions.

Consequently, measurements are in many cases recommended to get reliable values for the airtightness of a building element. The measured values must however be regarded as an indication, since in many practical situations, the workmanship, the presence of joints, the assembling tolerances,... have a major influence on the airtightness.

Proposals for a good practice from the point of view of airtightness should eliminate, as far as possible, these uncontrollable factors (e.g. plastering is safer than a 'good' pointing up of a wall).

1. AIR LEAKAGE MEASUREMENTS ON MASONRY WALLS

1.1. Measurement set up (fig. 1)

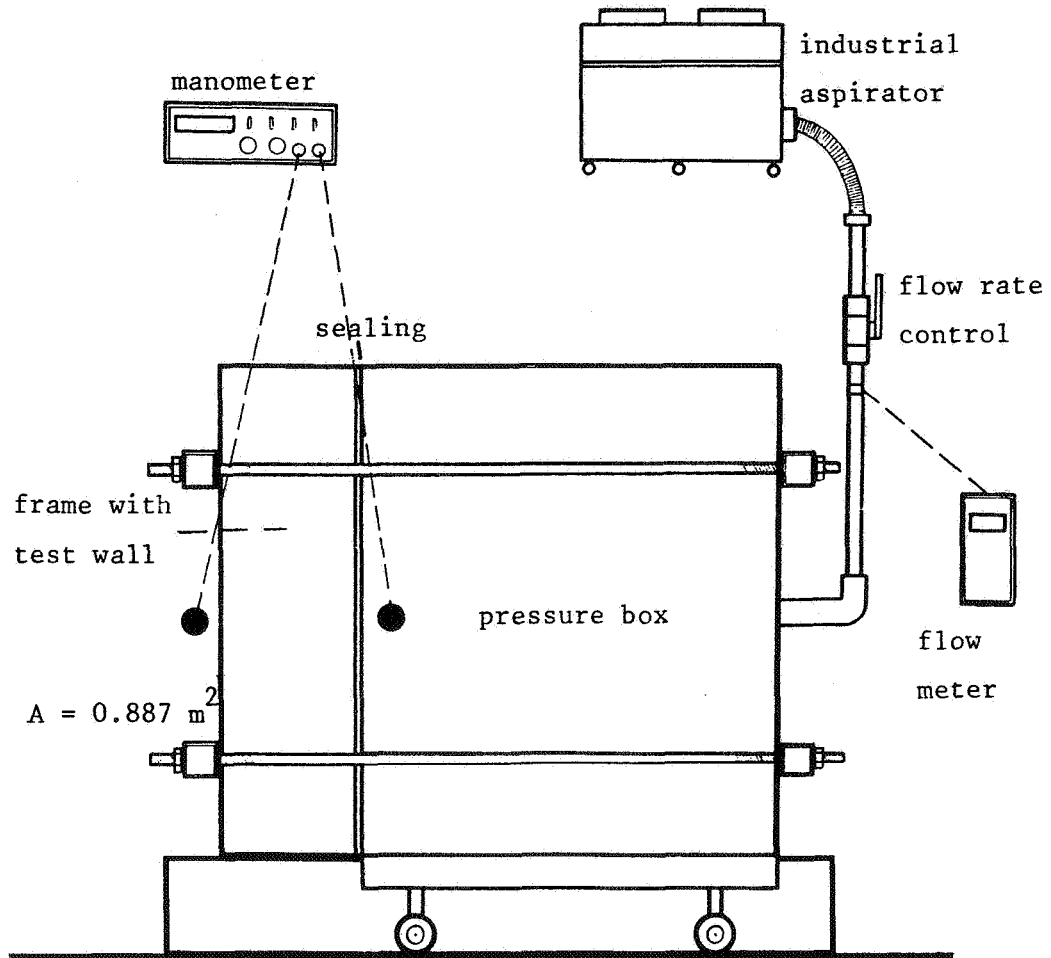


fig. 1, measurement set up

flowmeter : rotameter 1416 U10 (0-40 m/s),
Wilh. Lambrecht GmbH

manometer : micromanometer FC12 (0-20 Pa, 0-200 Pa),
Furness Controls Ltd.

The airflow through the test wall is measured at several pressure differences (at least 15) from 0 to 200 Pa, with accent on the low pressure differences (0 - 20 Pa).

1.2. The test walls

Following walls have been measured :

outer leaf

- brickwork
- brickwork
- concrete blocks

the variable parameters that are examined :

- workmanship
- pointing of the joints

inner leaf

- lightweight brickwork
- hollow concrete blocks
- cellular concrete blocks
- sandlime bricks

the variable parameters that are examined :

- pointing of the joints
- plastering of the inner leaf
(1 cm gypsum plastering on the inside)

1.3. Processing of the measurements

An exponential curve is fitted through the measurements (p_i, q_i) using a least squares technique :

$$q = a \cdot \Delta p^b$$

q = air flow through the test wall (m³/m²s)

Δp = pressure difference (Pa)

a, b = calculated coefficients,

$$0.5 < b < 1,$$

$b = 0.5$: fully turbulent flow

$b = 1$: laminar flow

1.4. Example of a measurement

Test wall : inner leaf, hollow concrete blocks
 (39 x 19 x 14 cm), $\rho = 954 \text{ kg/m}^3$

measurement	pressure difference (Pa)	air flow (m ³ /m ² s)
1	2.0	4.90 E-4
2	3.2	7.69 E-4
3	5.2	1.10 E-3
4	8.8	1.82 E-3
5	16.4	2.98 E-3
6	24.8	4.12 E-3
7	33.4	5.17 E-3
8	43.6	6.33 E-3
9	54.7	7.17 E-3
10	65.0	8.33 E-3
11	79.0	9.68 E-3
12	95.4	1.12 E-2
13	114.1	1.25 E-2
14	134.3	1.44 E-2
15	150.0	1.58 E-2
16	182.0	1.84 E-2
17	198.1	1.96 E-2

$$q = 3.09 \text{ E-4} \cdot \Delta p^{0.79} \text{ m}^3/\text{m}^2\text{s}$$

$$r^2 = 0.9994$$

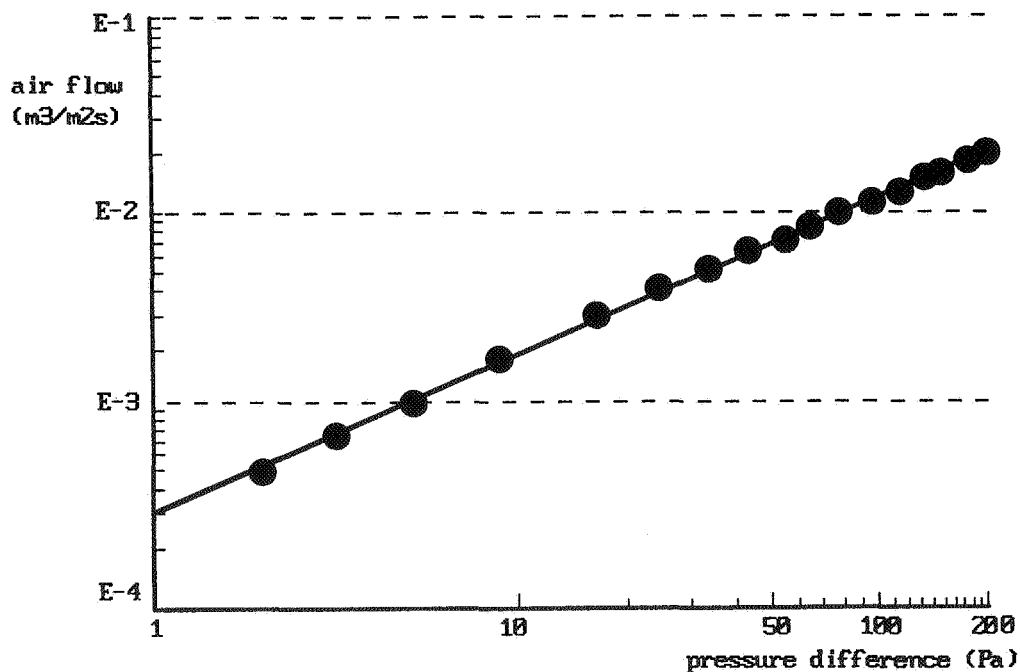


fig. 2, air flow as function of the pressure difference

1.5. Overview of the results

The air flow is given as :

$$q = a \cdot \Delta p^b$$

q = air flow through the wall (m³/m²s)
 Δp = pressure difference (Pa)
a, b = tabled coefficients

dimensions : length x height x thickness (cm)

1.5.1. Outer leaf, brickwork

dimensions : 19 x 9 x 4.5 cm

	a	b
no pointing, bad workmanship	2.7 E-4	0.69
no pointing, good workmanship	8.4 E-5	0.75
pointing of the joints	2.9 E-5	0.80
	3.0 E-5	0.79

1.5.2. Outer leaf, brickwork

dimensions : 19 x 9 x 6.5 cm

	a	b
no pointing, bad workmanship	6.0 E-4	0.68
no pointing, good workmanship	1.3 E-4	0.71
pointing of the joints	3.0 E-5	0.81
	2.9 E-5	0.82

1.5.3. Outer leaf, concrete blocks

dimensions : 19 x 9 x 9 cm

	a	b
pointing of the joints $\rho = 1955 \text{ kg/m}^3$	1.2 E-4	0.88
pointing of the joints $\rho = 1927 \text{ kg/m}^3$	1.6 E-4	0.86
pointing of the joints $\rho = 1881 \text{ kg/m}^3$	2.3 E-4	0.82

1.5.4. Inner leaf, lightweight brickwork

dimensions : 29 x 14 x 14 cm

	a	b
no pointing	2.2 E-3 3.5 E-3	0.59 0.57
pointing of the joints	2.4 E-5 1.7 E-5 1.4 E-5	0.72 0.81 0.82
one side plastering	3.1 E-7 2.3 E-7	0.96 0.97

1.5.5. Inner leaf, hollow concrete blocks

dimensions : 39 x 19 x 14 cm

	a	b
no pointing		
$\rho = 987 \text{ kg/m}^3$	3.3 E-3	0.58
$\rho = 954 \text{ kg/m}^3$	4.2 E-3	0.56
$\rho = 910 \text{ kg/m}^3$	5.0 E-3	0.55
pointing of the joints		
$\rho = 987 \text{ kg/m}^3$	1.6 E-4	0.91
$\rho = 954 \text{ kg/m}^3$	3.1 E-4	0.79
$\rho = 910 \text{ kg/m}^3$	5.0 E-4	0.70
one side plastering		
$\rho = 987 \text{ kg/m}^3$	2.9 E-7	0.96
$\rho = 954 \text{ kg/m}^3$	2.2 E-7	0.95
$\rho = 910 \text{ kg/m}^3$	2.6 E-7	0.97

1.5.6. Inner leaf, cellular concrete (glued)

dimensions : 60 x 24 x 14 cm

	a	b
no pointing	1.9 E-3 1.2 E-3	0.61 0.62
pointing of the joints	8.0 E-5 8.5 E-5	0.64 0.63
one side plastering	3.4 E-7	0.97

1.5.4. Inner leaf, sandlime bricks

dimensions : 29 x 14 x 14 cm

	a	b
no pointing	2.7 E-3 3.5 E-3	0.61 0.57
pointing of the joints	1.9 E-5 1.5 E-5	0.75 0.80
one side plastering	2.5 E-7	0.95

2. CONCLUSIONS

2.1. The walls can be divided in two groups :

- walls built up using airtight blocks (brickwork, sandlime bricks) ;
- walls built up using airopen blocks (concrete blocks, cellular concrete blocks) ;

In the first case, leaks have a major influence (e.g. not completely filled joints in unplastered brickwork). Pointing of the joints leads to an important increase of the airtightness of the wall ; the airtightness is mainly determined by the shrinkage cracks between brick and mortar. Plastering of the inner leaf is nevertheless recommended to obtain a satisfactory airtightness.

In case of airopen blocks, pointing of the joints has a minor influence on the airtightness. The obtained airtightness is always insufficient. Plastering is therefore a necessity when using these blocks as inner leaf. Attention must be paid to avoid air leaks when wall sockets or switches are fixed in the wall.

2.2. Recommendations

Out of these measurements can be concluded that plastering of the inner leaf of a cavity wall is always recommended to obtain a sufficient airtightness of the construction. The plastering of the inner leaf can eventually be replaced by a cement rendering on the cavity side of the inner leaf (fig. 3), (fig. 4).

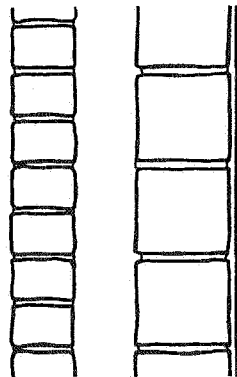


fig. 3, plastering

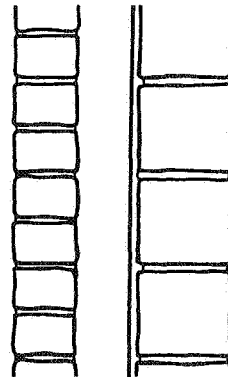


fig. 4, cement rendering

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POSTER P8

CONDENSATION DAMAGE TO TIMBER FRAME HOUSING

DR. S.J-M. DUDEK, MR. G. VALENTINE

Building Science Section
School of Architecture
University of Newcastle upon Tyne
Newcastle upon Tyne
NE1 7RU
United Kingdom

SYNOPSIS

This paper presents and discusses results of moisture transfer into timber frame constructions. The two mechanisms of transfer are diffusion and bulk air movement. Three defects in construction were monitored, punctured vapour barrier, continuous path via an electrical socket and discontinuities at junctions. The study has shown that, under steady-state conditions condensation can take place, while under varying conditions both condensation and evaporation occur. This second case is typical of the building in use, and can prevent high levels of moisture existing in timber components.

INTRODUCTION

The economic climate that has existed in the U.K. in recent times has enabled timber-frame construction to establish a respectable foothold in the U.K. house building market. At the expense of "traditional" construction techniques. Inevitably this has led to criticism of timber frame, some perfectly justified and others less so. The main criticism concerns the likely damage to softwood caused by high moisture content; the source of this moisture being water vapour in the internal air passing into the construction and then condensing somewhere within (Interstitial condensation).

Experimental studies, both at Princes Risborough Laboratory (7) and Newcastle have shown that, under certain environmental and constructional conditions, condensation will occur. However, to infer from this statement that timber frame is at risk from rot is not to fully understand the conditions under which these experiments were performed. For ease of repetition and convenience, steady-state conditions are often applied, either on one or both sides of the construction. Clearly, within the U.K. climate, the external conditions are anything but steady-state and the internal environment also varies with peaks and troughs of moisture production and temperature.

The real situation is complex with periods where condensation can occur followed by periods where evaporation takes place. The net accumulation of moisture is unknown. This article describes a section of work undertaken at Newcastle University Building Science Section. Our primary interest is in the thermal integrity of timber frame and the condensation studies described form only part of a comprehensive study being financed by SERC/University/Darlington Borough Council. What our investigation has shown is that when there is a change of condition across the wall construction which causes condensation to cease, then evaporation takes place and redistribution takes place at a similar rate.

Before these results are presented, a brief description of the mechanisms involved and the experimental set-up will be given.

BACKGROUND

Moisture in the form of vapour can be transported through the fabric of buildings by two mechanisms:

- (i) Diffusion
- (ii) Bulk air movement (air leakage).

Much attention has been focussed in recent years on the moisture transport problem, especially in buildings with substantial structural timber components. Several studies have addressed the problem rationally (1-7), each in turn contributing to our understanding. However, an absolutely reliable predictive method cannot be deduced because of:

The variation in materials vapour resistance value with temperature and humidity cycles,

The variation of the buildings' internal vapour pressure due to occupant factors,

The variation in standards of construction workmanship,

Uncertainties about the timber moisture content durational threshold for fungal growth.

The theory is as yet unrefined, which necessitates recourse to experimental methods to determine in-service moisture status of the timber components.

TESTING

The present study shows the results of monitoring the moisture content of one full-scale timber-frame wall, Figure 1, under various conditions of vapour barrier workmanship standards and under simplified environmental conditions. The construction was purpose-built full-scale in an environmental test chamber. The wall tested was a typical timber-framed inner leaf with:

1. 12.7mm plasterboard - joints taped and filled,
2. 500 gauge polythene vapour barrier,
3. 97 x 44mm softwood studs with 100mm fibrous insulation,
4. 8mm sheathing plywood (3 ply),
5. breather membrane.

Three typical vapour barrier defects were installed in a test wall:

punctured vapour barrier material ,

local destruction of the vapour barrier due to fitting a socket outlet,

discontinuities at junctions.

The environmental conditions were varied very simply in step fashion, as shown in Figure 2, over the test period of 20 days. In essence both the air pressure and vapour pressure differential were reduced independently, to investigate both the diffusion and air leakage processes.

The internal temperature was 21 ° C and the external temperature 2 ° C and this differential was held constant. Step changes in humidity were used to produce changes in vapour pressure differences and mechanical fan extraction used to create air pressure differences.

DEFECTS

Vapour Barrier Holes

Holes in the polythene vapour barrier 250mm and 500mm square were made at a height of 0.5m above ground floor skirting level, to represent possible workmanship errors.

These defects were vapour barrier discontinuities only with intact plasterboard and were subject to diffusion transfer.

Electrical Socket

An electrical socket was installed in the wall. The vapour barrier was cut neatly around the socket box, but not sealed to the electric cable. This afforded an air leakage path via the cable to the first floor joist space.

This defect involved both plasterboard and vapour barrier discontinuities and was subject to air leakage transfer and diffusion.

Junctions

A solid ground floor/wall junction and a timber first floor/wall junction were also studied. At the ground floor/wall junction there was a discontinuity between the polythene damp proof membrane and the polythene vapour barrier and a void in the mortar bed. The first floor/wall junction had the typical U.K. practice of discontinuity in the insulation and vapour barrier

at the junction. The leakage rates for these two floor junctions were 1.50 and 0.05 m³/hour at 7 Pascals respectively.

This defect involved both plasterboard and vapour barrier discontinuities and was subject to air leakage transfer.

RESULTS

The results of the experiment are presented in Figure 2. and show the variation in moisture content monitored on the inside surface of the plywood sheathing. No moisture content increase was recorded on the outside face of the plywood sheathing.

Vapour Barrier Holes

During constant vapour and air pressure differentials, the rate of increase in moisture content of the sheathing was 1.0% and 0.2% per day for the 500mm and 250mm holes respectively. A step change in air pressure caused no discernible change in the rates of increase. However, when the vapour pressure was step changed, a rapid decrease in moisture content took place.

Electrical Socket

The moisture content of the sheathing opposite the electric socket increased with time under both vapour and air pressure differences. A reduction in either pressure condition was accompanied by decreases in moisture content.

Junctions

The moisture content of the intermediate floor header joist never rose above 15% but the sole plate rose to 17%, the latter moisture contents reduced rapidly with zero air pressure differences.

CONCLUSIONS

The following conclusions can be drawn:

Interstitial condensation occurs on the plywood sheathing adjacent to vapour barrier holes. On removing the principal driving force, vapour pressure difference, evaporation and redistribution takes place.

Bulk air movement into the structure causes condensation to take place on the plywood adjacent to the air leakage path. Resulting in an increase in moisture content of the sheathing. When either vapour or air pressure differentials are reduced, then a decrease in moisture content takes place.

Bulk air movement through the construction causes local increases in moisture content of plywood, but acts to increase evaporation when humidity levels of the moving air are low.

This study has shown that, under steady-state conditions, condensation can take place within timber frame constructions. However, when varying conditions apply, both condensation and then evaporation can take place. Under real conditions, both internal and external conditions vary independently, providing periods of condensation and then evaporation which do not significantly alter the moisture content of the timber components.

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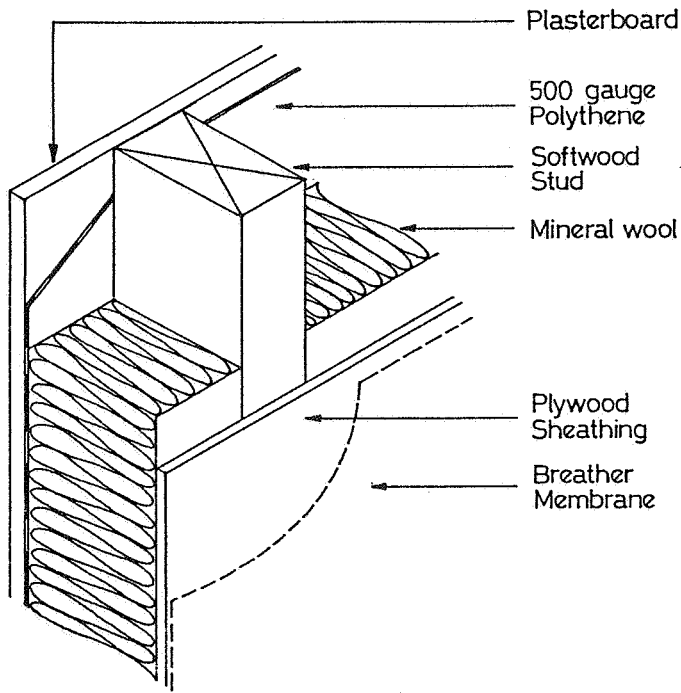


Figure 1 - The wall details.

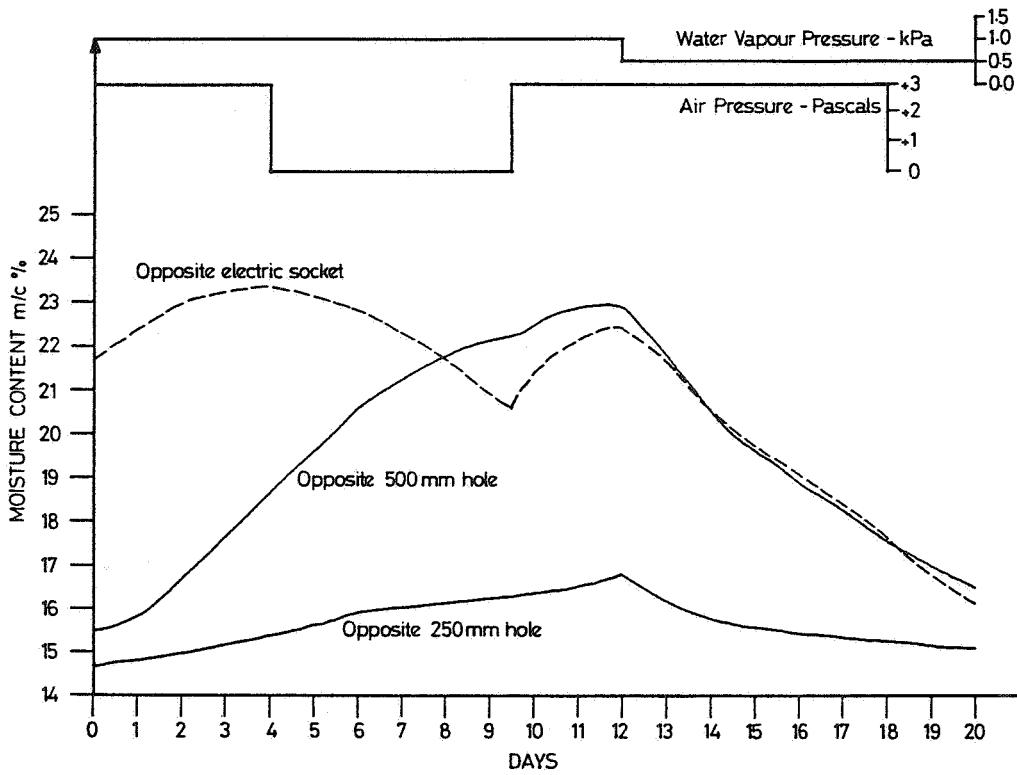


Figure 2 - Moisture content of plywood sheathing.

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

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POSTER P9

BUILDING CODES DESIGNED FOR ENSURING
GOOD INDOOR AIR QUALITY

R.H. FERAHIAN, ACGI, DIC, M.Sc.(Eng), MICE, M.ASCE.ING.

Consulting Engineer
4998 Maisonneuve, #1416
Westmount
Quebec
H3Z 1N2
Canada

ABSTRACT

All the findings about indoor air quality is of little use to the average citizen, if they are not applied and translated into rules incorporated in our building codes for the design, construction, and last but certainly not least maintenance of our buildings. And scientifically based up-to-date codes are not much use if they are not backed by strict, honest, and competent building inspectors. Recommendations are made for improvements in building codes to ensure good indoor air quality by concentrating, but not exclusively, on ventilation. Among the factors considered are: ensuring the good quality of the air intake, ensuring against its contamination by exhausts of the building or adjacent buildings, ensuring that energy conservation measures do not compromise the quality and quantity of the required ventilation air, and ensuring good maintenance of the building services that determine the quality of the ventilation air throughout the lifetime of the building necessary for the health of the tenants. Our laws must ensure good air quality in our living and working habitat as an environmental human right with right of access to information necessary for citizens to determine the quality of their indoor air environment.

1. Introduction

Indoor air quality is a function of the quality of the outdoor air, the percentage of the outdoor air in the ventilation air, design characteristics of the Heating, Ventilating and Air Conditioning (HVAC) system, structural and non-structural materials used in the building, its furnishings, the use and activities within the building, and the age, maintenance and management characteristics of the building.

Naturally building codes can not apply to all these parameters where either other bylaws or education must ensure good air quality indoors. One thing building codes can do is to ensure that the air entering the building is of good- or at least of acceptable quality. A related requirement would be to ensure that no toxic elements enter the building's habitable spaces whether through the basement walls or floor or from the other parts of the building's structural or non-structural elements. A good example for this latter category is radon gas (U.S. Department of Energy, 1986). No codes known to the author ensure against this latter serious cause of indoor air pollution and they should.

1.1 Quality of the Out-door Air

To ensure good indoor air quality, it is essential to first ensure that the outdoor air is at least of acceptable quality as defined for example by ASHRAE Standard 62-81. But how often is the outdoor air tested to verify this? Many papers reporting pollutant measurements indoors, simultaneous measurements are not reported for the outdoor air. Building permits should not be granted before acceptability of the outdoor air is demonstrated. Some Standards, like ASHRAE 62-81 specified that air cleaning devices must be used to bring the outdoor air to acceptable quality (5,6).

1.2 Contamination of the Fresh Air Intake

No overall diagnosis of the problems of the ventilation system and the indoor air quality in buildings can be made without information on the location of the fresh air intakes and exhaust outlets and the percentage of the outdoor air in the ventilation air. Yet in many papers on indoor air quality in buildings with prolonged complaints from occupants, this vital information has been lacking or unknown. In one case, even the courts did not ensure access to this vital information (6).

Short-circuiting of the fresh air intakes with exhausts of the building or adjacent buildings or contamination of the fresh air intakes due to badly chosen locations, warned against in most codes is a more common cause of indoor air pollution than is suspected or admitted (3-6). That winds at the site may cause such a contamination due to their aerodynamic interaction with the building under unfavourable atmospheric conditions is not specifically warned against in the codes and needs to be. A critical analysis of this cause of indoor air pollution and requirements of the Canadian and ASHRAE Standards are given elsewhere (4,5).

Contamination of fresh air intakes of buildings with exhausts takes a special dimension of urgency when the exhaust is from an area housing PCB-cooled transformers and/or capacitors, because in case of fire due to incomplete combustion of PCBs, dioxins and furans are produced - among which are some of the most toxic compounds created by man. Recent examples and recommendations are given elsewhere (5).

1.3 Energy Conservation Measures and Indoor Air Quality

Energy conservation measures introduced over the last decade have increased the airtightness of our buildings and decreased the percentage of the outdoor air in the ventilation. In earlier papers (3-6) concern was expressed

ssed about the adequacy of the minimum ventilation requirements when not backed by comprehensive air quality criteria and health research. Also questioned was the suitability of accepting contaminant concentrations of one-tenth of the Threshold Limit Values for general environmental conditions when their synergistic effects are not known. These were of special concern for complexes with sealed windows and smoking allowed therein and under the solely "economically" based practice of air recirculation and switch-off of ventilation after work hours. The problems encountered in one such complex together with the corrective measures effected are given elsewhere (3).

The real economics of energy conservation must include the long-term social costs and potential disadvantages of these measures on our health and well-being. Our codes must err on the side of protecting the health and welfare of the citizens. Hence, the objections against the reduction of the fresh air intake in our buildings as advocated by ASHRAE 62-81 vis-a-vis its predecessor ASHRAE 62-73 (1,2), a trend hopefully reversing with the most recent ASHRAE recommendations (5,6). But, unfortunately not all cities require compliance with the most recent ASHRAE recommendations and standards, if at all. In one extreme case in Birmingham, Alabama, in a three-storey office building with nonopenable windows after continued health complaints from the occupants, investigations revealed "to conserve utility costs the building owner had elected not to install outside make-up air ducts on the building's HVAC system" without having contravened the local building bylaws! (7).

Switch-off of Ventilation Fans

The effect of interrupting ventilation fans is not well documented. ASHRAE Standard 62-1981 provides guidance for interrupting the use of outdoor air when buildings are used intermittently. The nature of the contaminants, however, must be known. If they are result of outgassing of material and other sources within the building, it must be ventilated prior to occupancy. Turning off ventilation fans in apartment buildings, especially at night when all the tenants are in is in contravention of the ASHRAE Standard. Also turning off exhaust fans servicing the bathrooms can be an added source of indoor air pollution and odours. Moreover, fans are sometimes turned off under the guise of energy conservation to coverup malfunctions in the HVAC system such as inadequate temperature control at peak loads (5,6). For apartment buildings, our codes must leave no doubt for the need of uninterrupted functioning of the ventilation system.

Complaints to the City of Westmount concerning the turning off at night till the early hours of the morning of the exhaust fans servicing the bathrooms and also the

building's air intake fans servicing the apartments through the corridors revealed that the City's Building Bylaws "are complied with when the ventilation equipment having a certain capacity is installed in the premises in question" but that the "Bylaw regulates design rather than maintenance". This "legal determination" communicated by the City Clerk regarding the "Bylaw concerning Health and Sanitation in Buildings" stresses the importance of the legal health of our Bylaws(5,6).

1.4 Updating of Building Bylaws

HVAC systems must be designed, constructed, installed and - not usually mentioned in our codes and ought to be - maintained in conformance with good engineering practice. In North America, reference is usually to ASHRAE's Guides, Data and Handbooks of Fundamentals. Naturally, this reference is to up-to-date practice. For health of its citizens, our governments must ensure that our building codes use the best and most current technology. Another example in Westmount - and unbelievably and unexcusably at that because it is one of the most affluent cities in the Montreal Urban Community if not Canada - in its Bylaw quoted above, reference for the design and construction of ventilation systems is still to ASHVE Guide Vol.17 dated 1939, a volume that ceased to exist in 1957!

1.5 Bad Maintenance and Indoor Air Pollution

Inadequate maintenance and nonchalant attitude of some building managers regarding the needed good air quality can be a serious cause of indoor air pollution. The ventilation in the corridors supplying the apartments in the building referred to earlier was in the past cut off for several weeks due to, among others, inadequate temperature control. The result was chemical smells caused mainly by a defective oil-fired boiler. Also until recently, the Saturday test runs of its emergency diesel-fueled generator caused diesel fumes to infiltrate the building's ventilation system because of the bad maintenance and/or inadequate ventilation of the locale of the emergency generator.

Some examples of bad maintenance of the HVAC system as a cause of indoor air pollution and its health consequences are well known such as Legionaire's disease and humidifier fever. Apart from faulty boilers, infrequent filter changes have obvious consequences. Others are not well known (5,6). A badly maintained swimming pool, specially one on the roof of a building, or an incorrectly designed and/or badly maintained plumbing systems can result in water leaks that are a host to algae and /or fungal growths in places unknown to the tenants

but that affect their indoor air quality. Badly maintained saunas can also be the cause for such growths in partition walls. If such micro-organisms are carried by the saunas ventilation system to exhaust near a fresh air intake of the building, other areas can be affected. Also such uncorrected leaks can lead to immediately dangerous circumstances as short-circuiting fires in circuit breakers in rooms housing PCB-filled transformers with even catastrophic consequences (5).

1.6 CONCLUSION

All the findings about indoor air quality is of little use to the average citizen, if they are not applied and translated into rules incorporated in our building codes for the design, construction, and last but certainly not least maintenance of our buildings. And scientifically based up-to-date codes are not much use if they are not backed by strict, honest and competent building inspectors.

The jurisdiction of our Clean Air Acts must be extended to cover the air indoors which may be more polluted than that outdoors. Good maintenance of the building systems that determine the health and safety of the occupants must be a mandatory part of our codes.

Our laws must ensure good air quality in our living and working habitat as an environmental human right with right of access to information necessary for citizens to determine the quality of their indoor environment. To this end, an Environmental Bill of Rights is essential.

1.7 Acknowledgement

The authour gratefully acknowledges reuse of some examples and material presented earlier in references 5 and 6 given below.

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POSTER P10

An Outline of DAMP - a KBS Diagnostic System

H.A. TRETOWEN

Building Research Association of New Zealand
Private Bag
Porirua
New Zealand

ABSTRACT

DAMP is an 'Expert System' or 'Knowledge Based System' (KBS) to aid diagnosis of causes of moisture damage found in buildings in New Zealand. This paper gives an outline of the current version of DAMP, which is still under development at the Building Research Association of New Zealand, operating in the CLASS language developed at University of Auckland with BRANZ support.

AN OUTLINE OF DAMP - A KBS DIAGNOSTIC SYSTEM

1. INTRODUCTION

DAMP is a rule-based computer system for diagnosing moisture problems in buildings. The term DAMP strictly refers to a formal knowledge base, which, in this case, is accessed via the CLASS language on a host computer (VAX 750). In practice, the term is also used more loosely to include the associated technical knowledge and experience concerning moisture behaviour.

The reasons for interest in "expert systems" is that they may be able to make experience available to the inexperienced, and that they will perform consistently without overlooking facts or interpreting them differently from one time to another. In the case of diagnostic systems, these advantages come at a cost to generality and reliability, because the knowledge is imperfectly developed.

DAMP considers three types of moisture problem:

- (a) Mildew growth for condensation
- (b) Stains
- (c) Rot

It operates interactively, asking questions until there are grounds for a diagnosis, or all feasible lines of enquiry are exhausted. There are several forms of on-line help. The system can cope with some uncertainty of answers, and will consider more than one feasible cause. Each interview can be recorded to a file, in full and/or in summary, and comments can also be included in the file.

DAMP is not at this stage released for use except within the Building Research Association of New Zealand.

2. The DAMP Knowledge Base

- : "Water is neither created nor destroyed (- building moisture always comes from somewhere)"
- : "Moisture is the necessary and sufficient condition for decay, corrosion" Anon.

The appearance of moisture in a building is the result of largely deterministic and well established physical process. In principle, programs to fully analyse the moisture state of a building are possible. For design purposes this may be a feasible option, although even in this case a full individual analysis might be unrealistic. As a diagnostic aid such an analysis cannot be applied, because the initial and boundary conditions for the problem are not known, and the actual building details are not fully known either. For reasons like these, DAMP is based largely on observed associations and qualitative data applicable in the New Zealand setting.

BRANZ 20y+ experience began with published literature, much of which is sound but some quite defective. A long-standing advisory service using human "experts" handle over 500-1000 NZ enquiries annually on moisture problems. At this level of enquiry it becomes possible and necessary to

look for common factors, and to exploit them if present. It has been noted that, in at least some cases, these experts could produce apparently correct diagnosis from brief descriptions. However, it is also noted that such cases often invoked some call on an extensive knowledge of building practice and occupant habits, sometimes triggered by minor cues in the description. These associations normally occur at subconscious level, and are rarely noticed unless very deliberately sought for..

"DAMP" has already evolved through several stages. In one form it was a student project on Expert Systems (Sachdeva 1985). At present a more comprehensive version is under development at BRANZ, using the CLASS language (Dechapunya, 1986, M. Buis et al 1986).

Conversion of this associative knowledge base into rules, began with a separation into 11 building types, 8 symptom types, 6 sources of water, and 6 moisture transfer mechanisms. A schedule of these groups is given in Table 2, and a diagnostic tree illustrating the general scheme is given in Figure 1 .

Rules have been established to date for only one building type - domestic. Simple combinatorial expansion, using Table 2, shows that these different building symptom types, sources and mechanisms can occur in about 300 possible combinations. However, potential users are not expected to know much about moisture sources or transfer mechanisms, but they can be reasonably asked about the patterns applying to their symptoms (eg, where the symptoms are seen; if, how, and when they vary) and some information about the building itself, and about the way it is used. The number of possible combinations using this data promptly runs into thousands.

DAMP is fortuitously saved from being overwhelmed by the fact that the matrix of combinations is only sparsely filled. Only some 10% - 25% of the possible combinations are considered to exist and to add usefully to diagnosis.

The DAMP Knowledge Base System firstly divides the moisture problems into three groups:

- (a) mildew &/or surface condensation
- (b) stains
- (c) rot

Guidance is also available to help a user decide which if any of these conditions they may have. (This illustrates the beginning of the uncertainty - if someone is not clear what the problem is, the chances of getting accurate symptom descriptions must be suspect also).

In the case of mildew/condensation, the age of the building is established, and then the location within the building. Age is important only to establish whether or not the building is "new". If so, the chances are that the problems arise from construction moisture, ie, the use of timber or concrete which was installed wet or has become wet from rain, dew, or spillages during construction. These reservoirs of moisture in most cases dry off in the first few months of use. Furthermore, it is not usual for other, occupant-generated, sources of moisture to have accumulated sufficiently to be troublesome at that stage. Division into various locations in the building follows. As one might expect, problems in one room will not usually have their origin in another, although it is possible for more than one room to be affected by some common factor,

notably the degree of heating and ventilating. These two items are key factors, and are the hardest to establish adequately. Occupants will clearly have no knowledge or interest in the real causes of mildew/condensation, which relate to local moisture and temperature conditions. These, in turn, depend on the temperature differences between indoors and outdoors, the amount of indoor moisture released, the amount of ventilation and the insulation level. Consequently, one must ask indirect questions concerning heating and ventilation practices, and make assumptions about how equipment is probably being used. DAMP has been designed to default to an assumption that heating and ventilation are not sufficient if there are not adequate alternate indicators.

Although it is usual for problems in one location not to have their origins far away, there are some notable exceptions. Leaks have always been notorious for appearing far from their origin, but at least they are at a lower height than the origin. But there is a class of problems leading to stains, mildew, or dripping on ceilings, where roof moisture comes from subfloor ground. This can occur in buildings with masonry veneer or stucco walls, or with through-vented linen cupboards, that allow subfloor air to pass to the roof space. In cold clear weather, this process carries huge quantities of water into the roof. DAMP is set up to detect these cases, giving appropriate repair advice.

The "stains" and "rot" options do not bother about building age and go straight to identifying the location of the problems. These options are not yet as fully developed as the "mildew" option. The "rot" option is particularly difficult, because rot seems to be a somewhat individualistic phenomenon, often arising from specific local details, or from gross inattention. There are however a number of strong clues in the location and especially the patterns of stains and rot, which help point to probable causes. Whilst any well-defined pattern is likely to be a pointer to a particular cause, the patterns DAMP looks for are geometric patterns (particularly those corresponding to the construction elements of the building, such as the location of studs), and whether the stains change with cold, with wet, or with time.

In Figure 2 is a representation of the decision tree used in preparing the "rot" option of DAMP. This option is illustrated as it is the simplest of the three options. Although very cryptic, Figure 2 should give some idea of how the process functions, with single, multiple, or zero conclusions being offered in various circumstances. Notice that even where a firm conclusion is indicated, there is still no detail on exactly where or how the moisture has entered. That information, plus confirmation of the diagnosis, must be supplied by direct inspection of the particular site.

There is a major difficulty in defining what a given Knowledge Base consists of. Figure 2 may be taken as a definition, at one level, of a section of the DAMP Knowledge Base. But this definition only specifies the names of the items and their interconnection, it does not detail the items in full. A complete definition of the Knowledge Base could be taken to be the full listing of knowledge data used by the computer system. But, in many cases, this knowledge is inseparable from the program which interprets it, and would then be a grossly inadequate definition. CLASS provides that the DAMP Knowledge Base (or any other knowledge base it may be working with) is quite separate from the program, and can be separately listed. But the meaning of the Knowledge Base even then is affected by how CLASS uses it, and, with the sheer bulk of the listing, this is still not satisfactory as a definition. This difficulty will become greater if these systems become capable of creating new solutions, rather than being largely decision trees as at present.

Sample Run

In an Appendix, is a sample run using DAMP. The example given is based on a real case, but is conducted to illustrate some of the support features of DAMP. (This example does not necessarily use the most recent version of the Knowledge Base.)

This example shows that it is possible to pick up from a previous interview, and alternatively asks whether the user wants some basic guidance. The 'yes' choices made here shows what sort of help is available. These are indicated in steps 1-6.

At step 7 it has been ascertained that the problem is mildew (or surface condensation, which is equated to mildew), and the age of building is sought to determine if construction moisture is likely to have contributed. In this example, construction moisture is not to blame.

Then the location of mildew is established (step 9). Had this been on interior surfaces, there would have been supplementary questions about the heating and ventilation of the house. But, since the problem was in a wardrobe, and in addition the room was not normally used, then the heating and ventilation are unlikely to be of influence.

At this stage DAMP concluded that it had enough evidence to form a diagnosis, and two possible conclusions are offered. In the real case, it was found that the cause was a roof leak, evidenced by water stains on the underside of roof tiles above the wardrobe.

An extension to the 'interview' is then illustrated in steps 13-15. At the end of step 13 we change the 'observed location of mildew' from 'wardrobe' to 'on external walls'. Note that DAMP then seeks some information on the heating and ventilation, concluding that these are adequate in this case, and the occupants should curb their moisture emission. Note particularly that the heating and ventilation questions are indirect. The truly relevant question is not asked as it is believed the interviewee is unlikely to know.

3. CONCLUSIONS

Some features of moisture-problem diagnosis in buildings can be achieved with reasonable reliability by rule-based systems, and one such system - DAMP - has been briefly outlined.

Whilst systems such as DAMP can be a useful aid, there are also a number of difficulties which are hampering their advance. These must be solved before the full potential of these systems can be realised.

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Factor	"Intuitive-Based" System (Human)	"Rule-Based" System (Computer)
Availability to date	available, (but few good experts)	not available
Reliability of diagnosis	high	variable
Limits (to extent of accessible knowledge)	unlimited	rigid limit
Flexibility (to cope with unexpected variations)	high	zero
Consistency of diagnosis	usually consistent	totally consistent
Recordability of case details	records often imperfect	records can be exact
User training needs	very lengthy	minor
Form of knowledge	associative	heirarchal

TABLE 1. COMPARISON OF TWO FORMS OF THE "DAMP" KNOWLEDGE BASE

<p><u>Building Types:-</u></p> <ol style="list-style-type: none"> 1. Houses 2. Multi-apartment 3. Office 4. School 5. Dry Process Manufacture 6. Wet Process Manufacture 7. Warehouse 8. Cold Stores 9. Swimming Pool Hall 10. Sports Hall 11. Laundry 	<p><u>Symptom Types:-</u></p> <ol style="list-style-type: none"> 1. Mould 2. Visible water 3. Water stains 4. Other stains - Tar Stains - Pattern Stains 5. Paint Blistering 6. Rot 7. Corrosion
<p><u>Schedule of Available causes:-</u></p> <p><u>Moisture Sources</u></p> <p>Construction moisture</p> <p>Ground water</p> <p>Rain leaks</p> <p>People (breathing washing cooking)</p> <p>Process moisture</p> <p>Pipe leaks</p>	<p><u>Transfer Mechanisms</u></p> <p>Air movement</p> <p>Seepage/capillary</p> <p>Sunshine/temperature changes</p> <p>Condensation</p> <p>Vapour diffusion</p> <p>Storage</p>

TABLE 2. SOURCES AND SYMPTOMS OF BUILDING MOISTURE

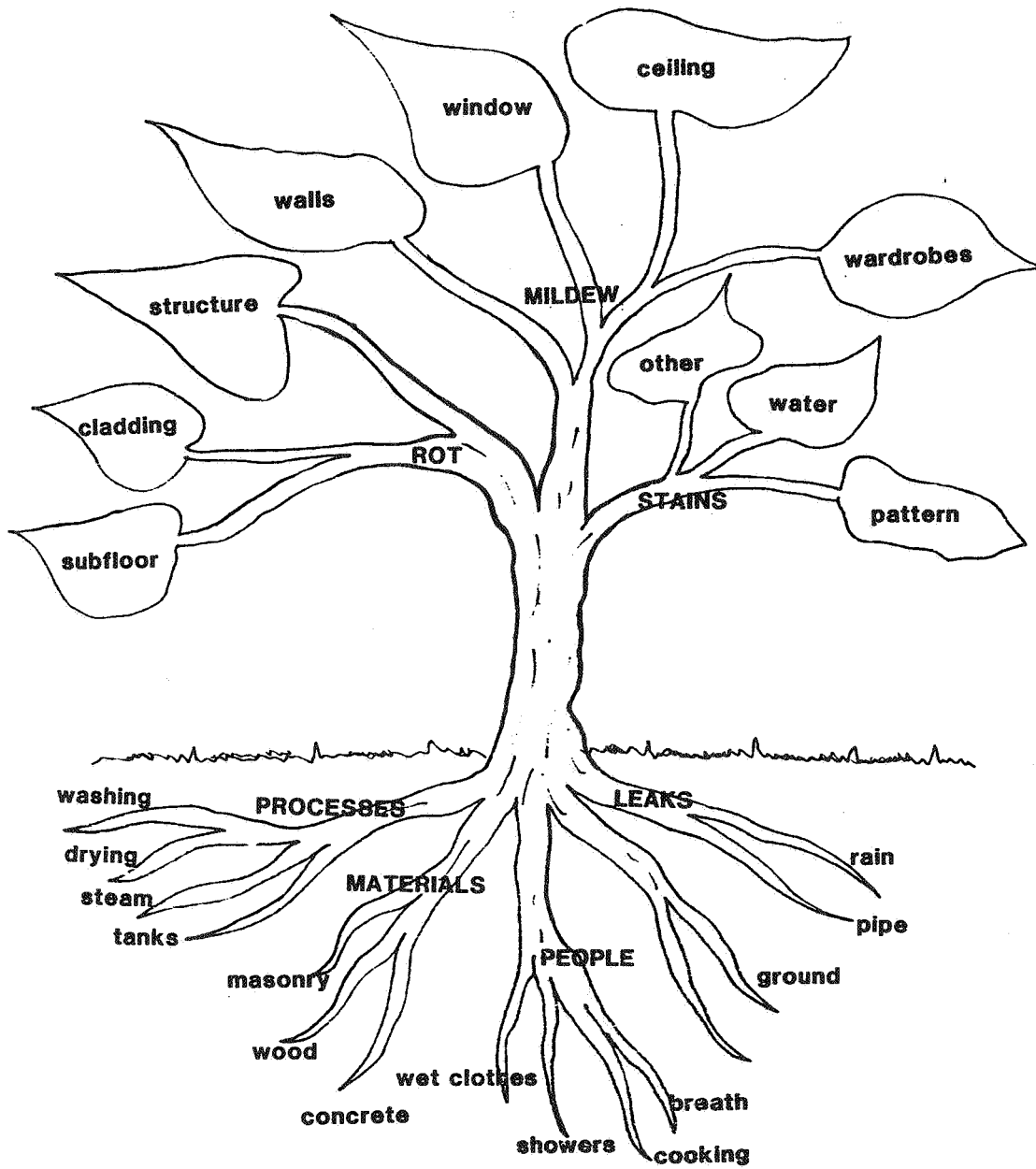
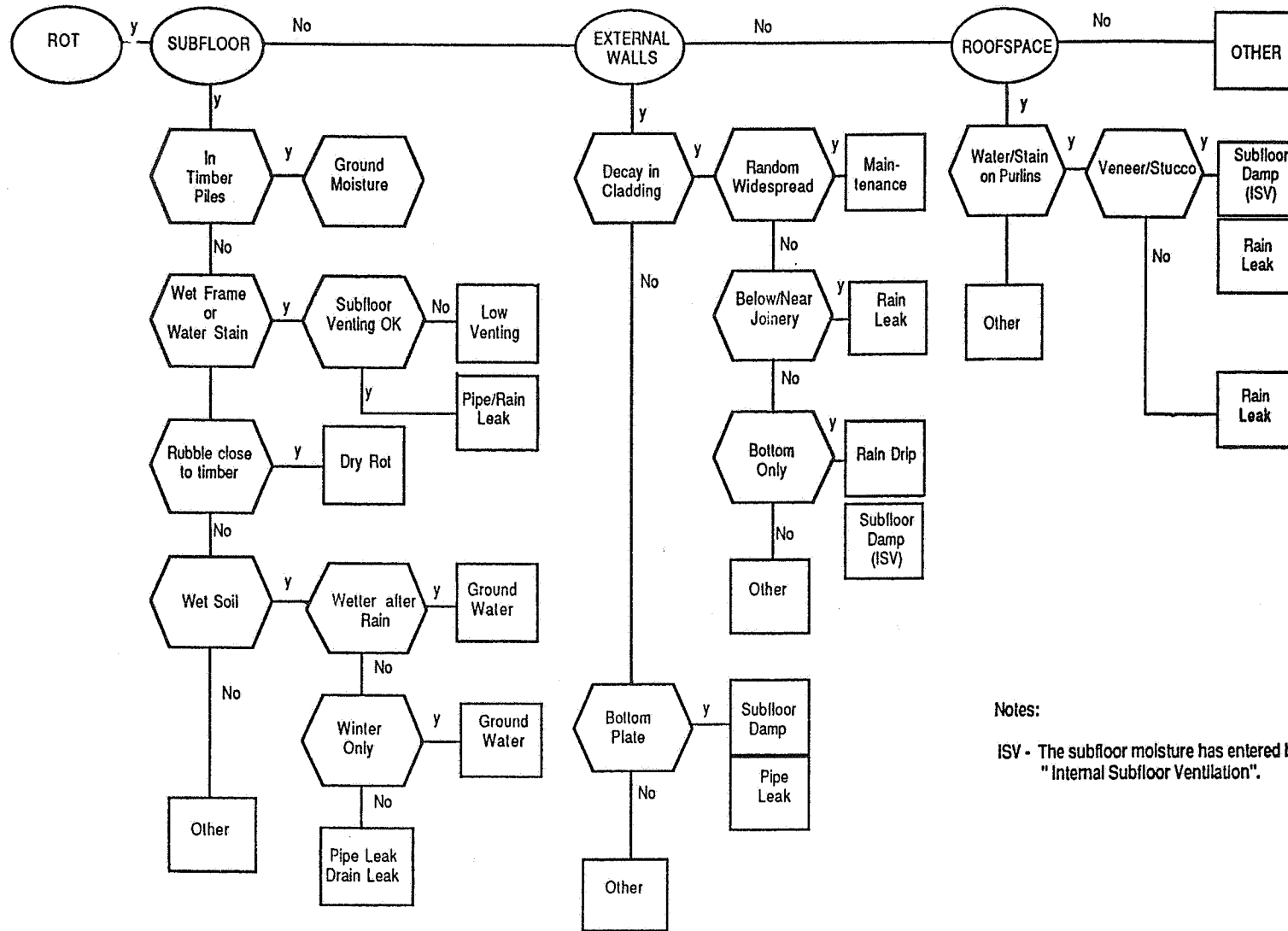


FIGURE 1 The Diagnostic Tree



Notes:
 ISV - The subfloor moisture has entered by "Internal Subfloor Ventilation".

FIGURE 2 Summary of present form of "Rot" option of "Damp" diagnostic rules

a sample case

DAMP KNOWLEDGE BASED SYSTEM

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At present BRANZ accepts no liability for the information contained in this knowledge base or any advice given during this consultation.

Do you wish to continue from a previous session [N] ? n

The DAMP system is intended to be used as a diagnostic aid to moisture problems frequently encountered in New Zealand houses.

The system will attempt to learn more about your problem by asking you questions about the problem. Once the system has enough information to determine the likely cause of your problem, it will display it, along with a discussion of the problem and a number of actions you can take.

--0--

Do you want further information about the DAMP system ? yes

How To Use The DAMP System

The DAMP System will try to learn about your moisture problem by asking you questions about your situation. It is important that you try to answer these questions as accurately as possible. If you do not know the answer to any question, you may type "UNKNOWN". The system will continue using other information.

DAMP will sometimes ask you to choose from a list of alternatives, such as the following:

- Do you want to choose:
- 1 - The first alternative.
 - 2 - The second alternative.

Please type the number of the appropriate choice >

You can type "1", "2" or "UNKNOWN" in response to this question.

DAMP will also ask you questions such as this:

Do you want further information about the DAMP System ?

You can type "YES", "NO", "Y", "N" or "UNKNOWN" to this question.
(All communication with DAMP can be either upper or lower case.)

Before you use the DAMP system, it will be useful to know some basic information about the house, such as its age, the type of wall material used, whether it is insulated. This will speed up the consultation process. If you do not know any of this information, just type "UNKNOWN" when you are asked a question about it.

Once the system has collected enough information to be able to make a judgement about the likely cause of your problem, it will display its conclusions to you. Each conclusion will identify the most likely cause, give some background information, and outline a number

of possible actions you can take. If you want further information about the findings you may ask for this also.

--1--

Do you want information about how explanation works ? n

--2--

Do you want information about how to change your answers ? n

--3--

Type the address of the building for reference (in one line).

> 123 noname road

Consultation Starts.

--4--

DAMP uses the symptoms you can see, and tries to match these with the causes which might apply, and where possible suggests the action that should be taken to remedy the problem.

DAMP recognises three main groups of symptoms:

- 1 - Mildew.
- 2 - Stains.
- 3 - Rot in Timber.
- 4 - Not sure.

Please type the number of the appropriate description > 4

--5--

The following symptoms are indicative of moisture problems:

Mildew is usually indicated by any of the following:

- The stain has fuzzy edges and is mainly one colour (usually black).
- The stain smudges when touched and there may be a musty smell in the area.
- The stain has fibrous growths on the surface (like microscopic plants or vines) when inspected closely.
- On glossy surfaces, mildew can be wiped or washed off, on matt surfaces it can sometimes be vacuumed off, but will regrow.

Stains caused by moisture may be indicated by:

- The stains do not look like fibrous growths and do not come off easily or spread when touched.
- The stains have sharp edges, and may have more than one colour

Rot in timber is usually indicated by any of the following:

- Wood is soft when pressed by a thumbnail or spongy when pressed by a finger.
- Patches of wood which have shrunk inwards.
- Any soft white fibrous growth over the wood.

Does your problem have any of the above symptoms ? y

--6--

Which of the problem types does the symptom suggest:

- 1 - Mildew.
- 2 - Stains.

- 3 - Rot.
- 4 - Not sure.

Please type the number of the problem that seems likely > 1

--7--

What is the age of the building:

- 1 - The building is less than 6 months old.
- 2 - The building is 6 - 12 months old.
- 3 - The building is 1 - 20 years old.
- 4 - The building is over 20 years old.

Please type the number of the appropriate age > 4

--8--

From the following description of floor:

- 1 - Slab-on-ground floor less than 12 months old.
- 2 - Slab-on-ground floor more than 12 months old.
- 3 - Suspended floor.

Please select description of floor >3

--9--

What is the location of the mildew:

- 1 - On the ceiling.
- 2 - On external walls.
- 3 - On internal walls.
- 4 - On the floor.
- 5 - In wardrobes or cupboards.
- 6 - On drapes.
- 7 - Other.

Please type the number of the mildew location > 5

--10--

Are damp items often stored in the wardrobe or cupboard ? n

--11--

Is the room / wardrobe in normal use ? n

Reference : 123 noname road

Determining the likely cause of the problem:

WALLS ARE INTERNALLY VENTED FROM SUBFLOOR SPACE.

Normally internal walls are not cold enough to allow mildew growth. But if they are vented internally from the subfloor - no longer a recommended practice - this not only brings moist subfloor air into the wall, but also cools the wall so that it collects mildew.

Action: Stop up internal wall vent openings.

Improvement should occur almost immediately.

Another possible cause is:

PIPE OR RAIN LEAKS.

Mildew requires moisture for survival, and usually this moisture is generated by occupants. If the space is not occupied then it is not likely that moisture will come from people, and rain or pipe leaks become the most likely source of water.

Action: Find the leak and fix.

Improvement should normally be seen within days or weeks.

--12--

Would you like to see some more technical information about heating, insulation and humidity ? n

--13--

Would you like to see a list of related publications ? n

Would you like this session to be saved as a case study for BRANZ [Y]? y

[change] Change an answer to a question
[knowns] Show the answers given to questions
[comment] Write a comment to BRANZ
[run] Start another session
[help] Provide more detailed information about options
[?] Display this menu

[exit/quit] Exit the system

Command > knowns

The following data has been input:

=====

--0-- wantInstructions = true
--1-- wantExplanationHelp = false
--2-- wantChangeHelp = false
--3-- reference = 123 noname road
--4-- usersProblemType = notSure
--5-- hasSymptom = true
--6-- theSymptom = mildew
--7-- age = over 20 years
--8-- usersAgeOfConcreteFloor = none
--9-- location = wardrobe
--10-- wetItemsStored = false
--11-- roomInUse = false
--12-- wantTechnicalInformation = false
--13-- wantBibliography = false

Command > change

Enter the answer number(s) [type "?" for list of numbers] > 9

--9--

What is the location of the mildew:

- 1 - On the ceiling.
- 2 - On external walls.
- 3 - On internal walls.
- 4 - On the floor.
- 5 - In wardrobes or cupboards.
- 6 - On drapes.
- 7 - Other.

Please type the number of the mildew location > 2

--14--

Can you indicate some of the features affecting the average ventilation of the space:

- 1 - The building is locked during the working day.
- 2 - The house is aired daily for more than 5 hours / day.
- 3 - The building is well ventilated in some other way.
- 4 - Not sure.

Please type the number of the appropriate ventilation > 1

--15--

We now need some information about the degree of space heating used. Since the information ultimately needed is not likely to be available, the following are indirect indicators:

- 1 - The building is centrally heated.
- 2 - Two or more nightstores are used.
- 3 - Heating is typically on for at least 4 hours per day (in winter) in the affected space.
- 4 - Temperature in the affected space is nearly always 6-7 degree C warmer than outside.
- 5 - Temperature in the affected area is often less than 6-7 degree C warmer than outside.
- 6 - Only limited heating is used.
- 7 - Unsure about the heating used.

Please type the number of the appropriate indicator > 2

Reference : 123 noname road

Determining the likely cause of the problem:

TOO MUCH MOISTURE.

It is unusual to get mildew when the heating and ventilation are both sufficient. I have inferred that they are in this case. If so it is likely that the cause of mildew is that too much moisture is being released, from things such as:

- flueless gas, kerosine, or LPG heaters
- showers
- people
- indoor clothes drying

Or perhaps the insulation is not adequate where mildew has formed.

If you wish to look for further possibilities, then use CHANGE command to alter your replies to heating and

ventilation questions.

Would you like this session to be saved as a case study for BRANZ [Y]? y

[change] Change an answer to a question
[knowns] Show the answers given to questions
[comment] Write a comment to BRANZ
[run] Start another session
[help] Provide more detailed information about options
[?] Display this menu

[exit/quit] Exit the system

Command > exit

VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER P11

THE IMPORTANCE OF WIND BARRIERS FOR
WOOD FRAME CONSTRUCTIONS

SIVERT UVSLØKK

Norwegian Building Research Institute
Division Trondheim
Høgskoleringen 7
7034 Trondheim NTH
Norway

SUMMARY

The main goal of a research project on wind barriers was to get more information about the influence of wind pressure on the heat loss from wood frame constructions. The project was divided into three parts: calculations, hot-box measurements and wind pressure measurements on a rotatable test house. The theoretical studies as well as the experimental investigations in the hot-box, have been restricted to one specific type of forced convection in the thermal insulation, called "anblåsning", i.e. the interchange of air between the insulation and the airspace between the wind barrier and the outer cladding. The results of the project show the importance of protecting the insulation layer with a wind barrier to achieve full effect of the insulation in wind exposed constructions. The measurements indicates that heat loss caused by this type of forced convection, can be three to ten times higher than calculated.

1 INTRODUCTION

Recommended airtightness of wood frame constructions are usually achieved by use of an air barrier, i. e. a polyethylene film, on the hot side of the thermal insulation. This barrier may be mounted with a minimum of joints and it is relatively easy to achieve good protection against airflow through the constructions as measured by use of the pressurisation method. It is, however, still necessary to protect the thermal insulation by use of a wind barrier on the cold side of the constructions. In this project concerning wind barriers the theoretical studies as well as the experimental investigations in the hot-box, have been restricted to one specific type of forced convection in the thermal insulation, called "anblåsning", i.e. the interchange of air between the insulation and the airspace between the wind barrier and the outer cladding. The project has been funded by The Royal Norwegian Council for Scientific and Industrial Research as well as 13 producers of wind barriers or thermal insulation.

2 WIND PRESSURE MEASUREMENTS

The windpressure measurements, which started in November 85, was necessary to get input values for the calculations and the hotbox measurements. Other goals were to obtain morecorrect wind pressure coefficients for use in air infiltration models and to study the possibility of reducing the pressure variations outside the windbarriers by connecting the airspaces behind the claddings and below the roof to a single pressure equalization chamber. This is of interest for reduction of wind induced infiltration in common constructions, but is also of special importance for developing simple constructions based on the dynamic insulation principle. A test house has been equipped with instrumentation for wind pressure measurements. By use of an electromotor the test house can be rotated to any desired position relative to the wind direction. The basic dimensions of the house are: Length 9 m, width 5 m, height to the top of the roof 6 m and roof angel 36°. The location of this house is on an open test area at the top of the Tyholt Hill in Trondheim.

By use of 20 pressure transducers (Furness) and a fast datalogging system (3530 ORION) the wind pressure at 20 points is recorded simultaneously. By exchanging the plastic tubes connected to the pressure transducers the wind pressure at 52 different points is measured.

Two groups of pressure points are located on a short wall and four groups on a long wall. The eight pressure points in each group are distributed along a vertical line, see Fig.1. In addition, the indoor pressure and the pressure in the middle of the attic are measured.

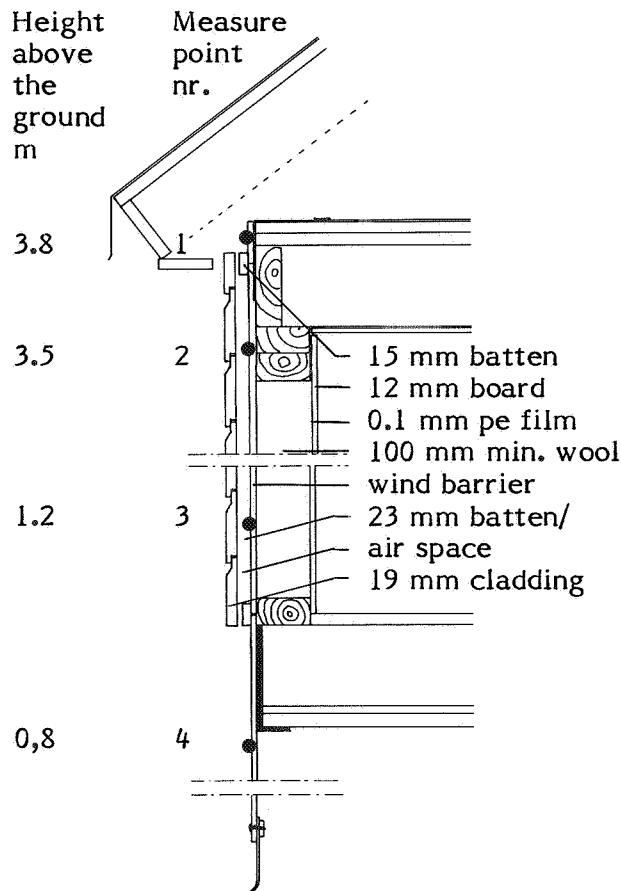


Figure 1.

Example of construction (variant 3) showing the location of measurement points for wind pressure. Only those corresponding to the diagrams are shown. In addition wind pressures have been measured in the attic and at three points on the outside of the wall sections.

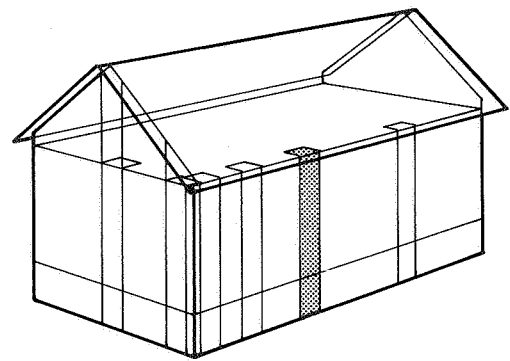


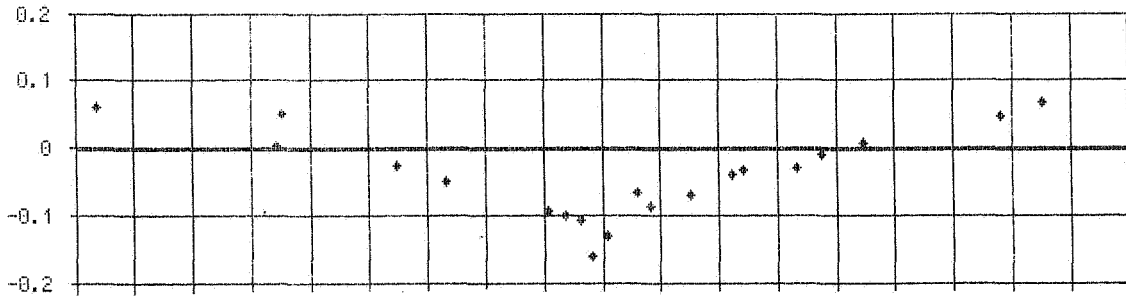
Figure 2.

The test house. Results for the hatched area are shown in the diagrams.

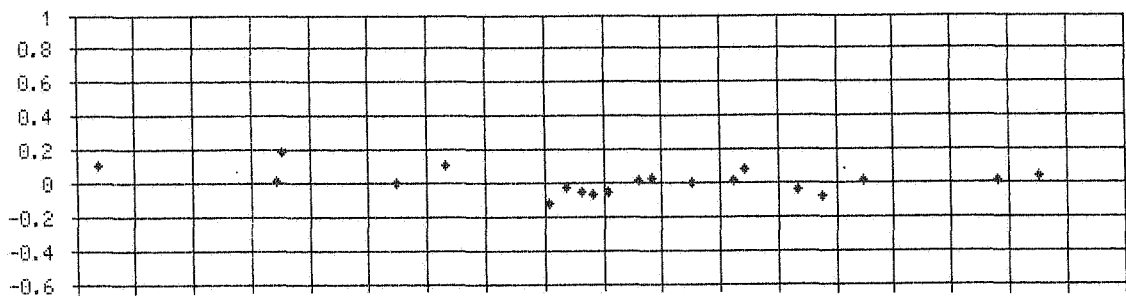
The static pressure measured 10 m above the ground in a mast on the roof, serves as reference for the pressure transducers. The dynamic pressure measured at the same place is used when calculating wind pressure coefficients. The wind pressure gradient coefficient is defined as the difference between the wind pressure coefficients of two points divided by the distance between them.

As the wind pressure behind the cladding will be influenced by construction details like the gaps at top and bottom of the airspace behind the cladding, it is necessary to do wind pressure measurements for various solutions as well as at various wind approach angles. Three variants have been investigated. Variant 3 is shown in figure 1. Variant 2 is identical, but with no wooden board on the under side of the roof edge. Variant 1 is identical with Variant 2, but without horizontal battens at the air space openings. Examples of results are shown in the diagrams 1 to 5.

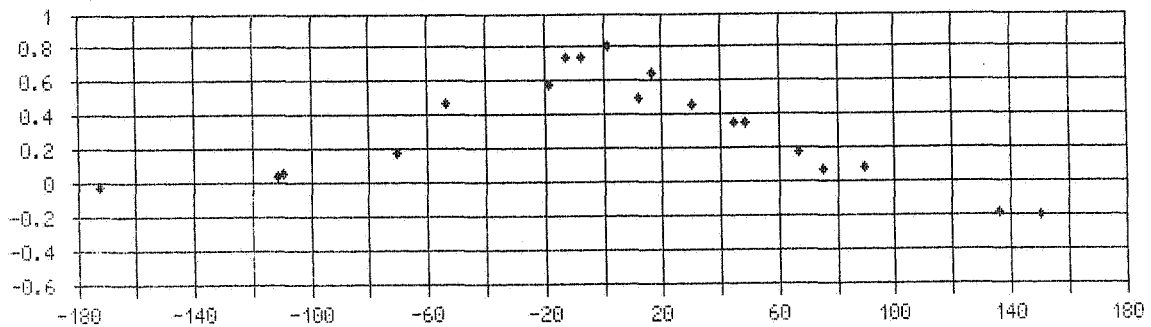
Wind pressure gradient coefficient in the air space, between point 2 and 3, m^{-1}



Wind pressure coefficient at point 1



Wind pressure coefficient at point 4



Wind approach angle

Diagram 1, 2 and 3.

Example of results from the wind pressure measurements. The diagrams show how the wind pressure gradient coefficient and wind pressure coefficients vary with the wind approach angle. (0° = perpendicular to the wall). The location of the measuring points are shown in figure 1 and figure 2.

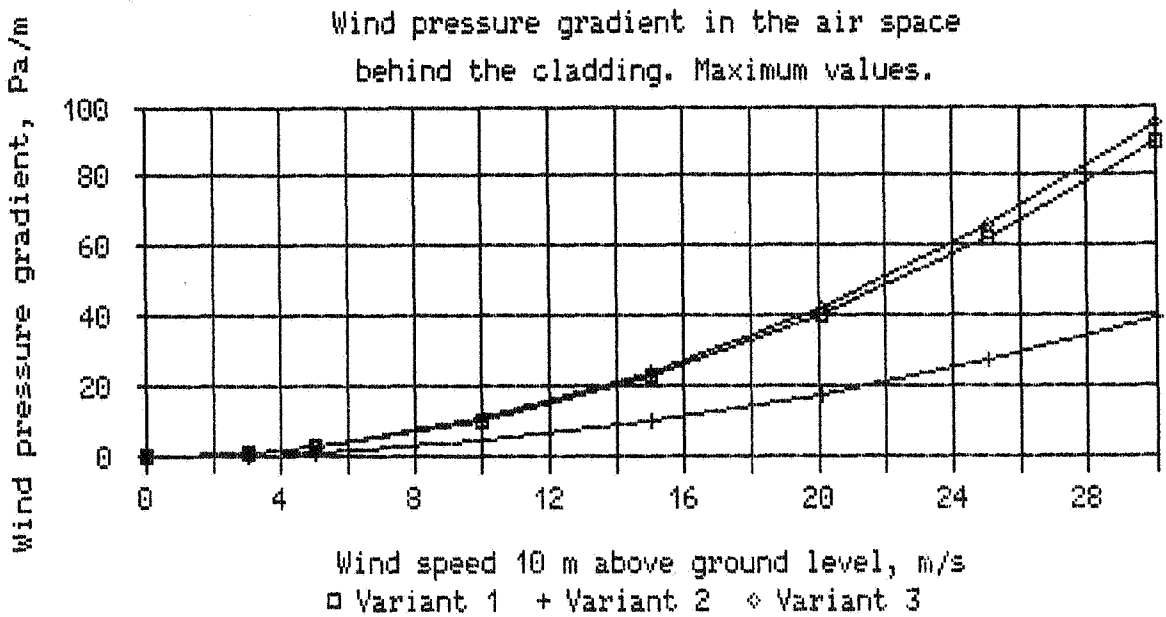


Diagram 4.

Estimated maximum gradients based on the wind pressure measurements. The wind pressure coefficients used are maximum values regarding both test section and wind direction.

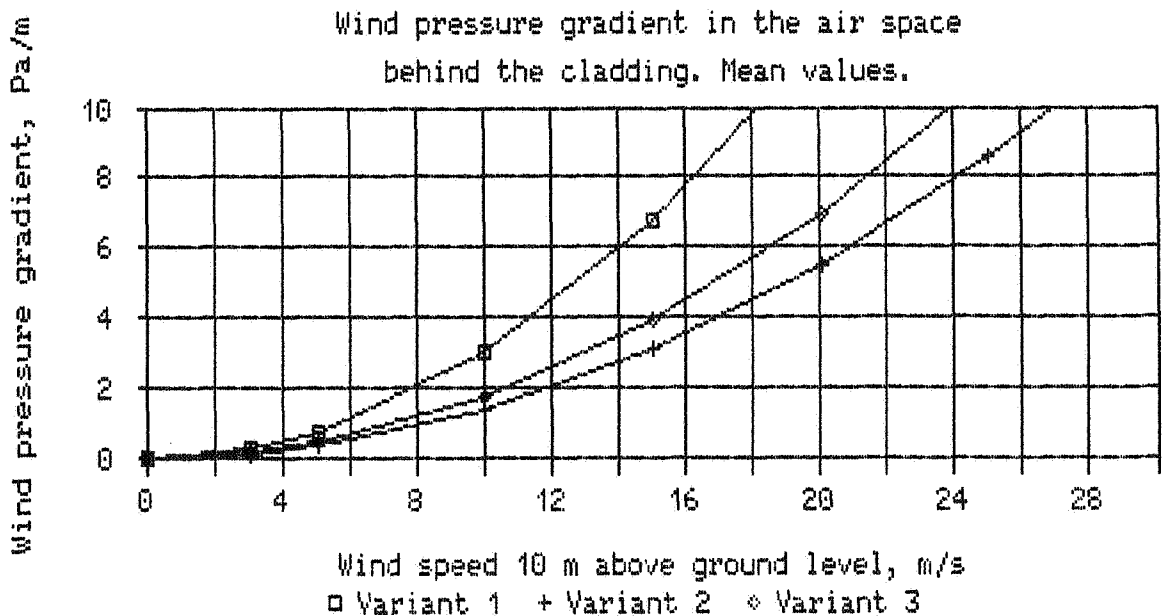


Diagram 5.

Estimated mean gradients based on the wind pressure measurements. The wind pressure gradient coefficients used are average values with regard to wind direction as well as to total wall area of the house.

CALCULATIONS

The interchange of air between the insulation and the airspace between the windbarrier and the outer cladding is caused by wind induced pressure gradients in the airspace, which normally has small openings at the top and bottom for moisture evacuation. In the mathematical model, based on references 2 and 3, the inside of the wall is assumed to be air tight, so that there is no airflow through the structure. Main parameters affecting this type of heat loss are pressure gradient in the airspace, air permeance of the wind barrier and permeability of the insulation. The computer program is used to estimate the pressure gradient in the airspace, the airflow in the insulation and the resulting heat loss through the wall.

HOTBOX MEASUREMENTS

To verify the theoretical model for the type of heat loss described previously, several hotbox measurements have been carried out on a timber frame wall of normal size. The guarded hotbox which is used has a measuring area of 2,45 m x 2,45 m. The test wall was insulated by a 150 mm thick layer of mineral wool and made as airtight as possible on the warm side by use of plastic film, tape and gypsum board. The forced convection was simulated by regulating vertical air flow in the space between the wind barrier and the outer cladding. The test program includes heat loss measurements at various air speed/pressure gradients without windbarrier and with 9 types of wind barriers. Both the calculations and the measurements show the importance of protecting the thermal insulation with a wind barrier to achieve full effect of the insulation in wind exposed constructions. Some results from the measurements are shown in diagrams 6 and 7.

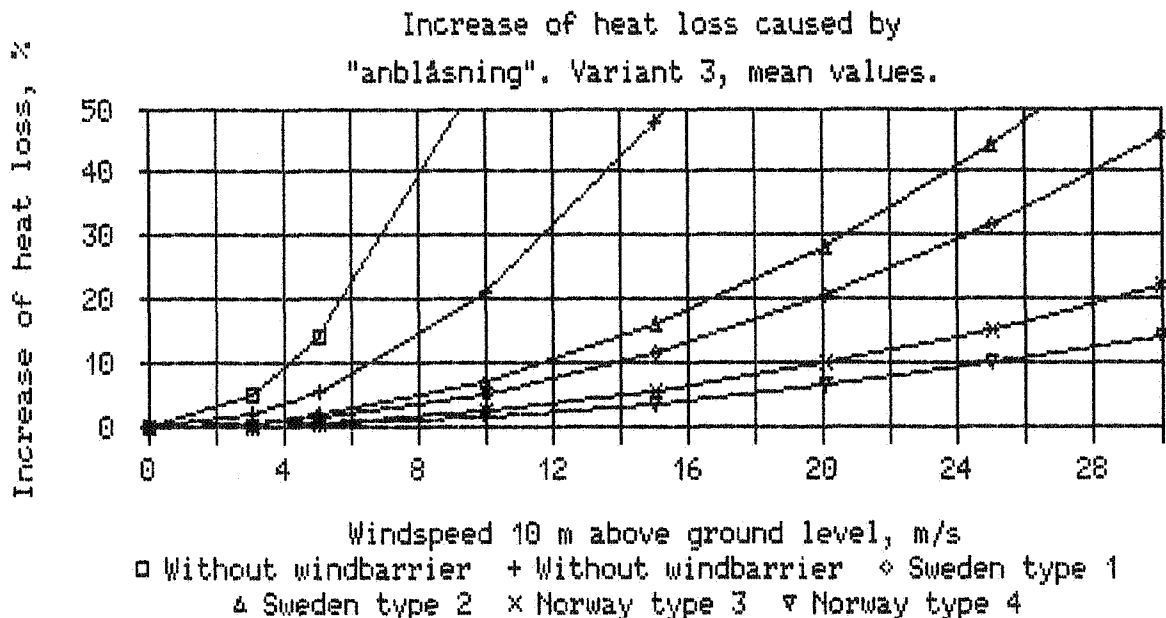


Diagram 6.

Estimated increase of heat transfer through a wood frame wall caused by "anblåsning" (see explanation). Air space and openings as shown in figure 1

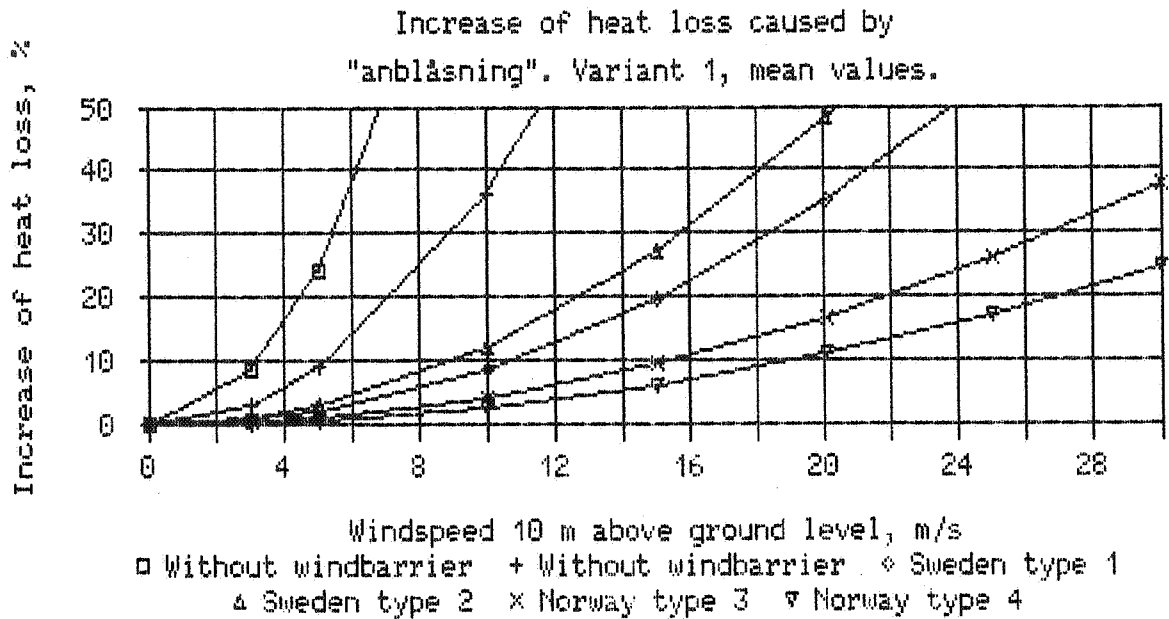


Diagram 7.

Similar to diagram 6 but applied to an other construction, variant 1. It is identical with variant 3, but there are no horizontal battens at the air space openings and no wooden board on the under side of the roof edge.

The estimations are based on the results shown in diagram 5 and on hot-box measurements on a wall with thermal insulation of 150 mm mineral wool. The measurements without wind barrier refer to two different ways of mounting the thermal insulation. The wind barriers type 1 and 2 are examples of wind barriers in common use in Sweden while type 3 and 4 represent the upper and lower limits of wind barriers used in Norway. The permeance of the four materials were $1.70 \text{ E-}5$, $1.5 \text{ E-}5$, $1.70 \text{ E-}5$, $0.22 \text{ E-}5$ and $0.06 \text{ E-}5 \text{ m}^3/(\text{m}^2 * \text{s} * \text{Pa})$ respectively.

Measured increase of heat loss is about two to five times higher than calculated. The main reason for this divergence seems to be the influence of the joints in the wind barrier and the fact that, more or less, there are some gaps and inhomogeneities in the insulation layer in real constructions.

During the hot box measurements only vertical joints in the wind barriers were included, while the horizontal joints at the sills were made air tight by use of tape. This was done to minimise the influence of possibly variations due to workmanship. Diagram 8 shows estimated values for normal constructions as well as for fictive walls with no joints. The estimations are based on the hot box measurements as well as data from ordinary leakage measurements on wind barrier materials and on full scale constructions including a normal amount of vertical and horizontal joints. The estimates are made for a wind pressure gradient in the air space of 10 Pa/m. As shown in diagram 8 the influence of the joint leakage varies widely and dominates compared with the material leakage for most types. The diagram illustrates the importance of considering both material and joint leakage data when choosing type of wind barrier.

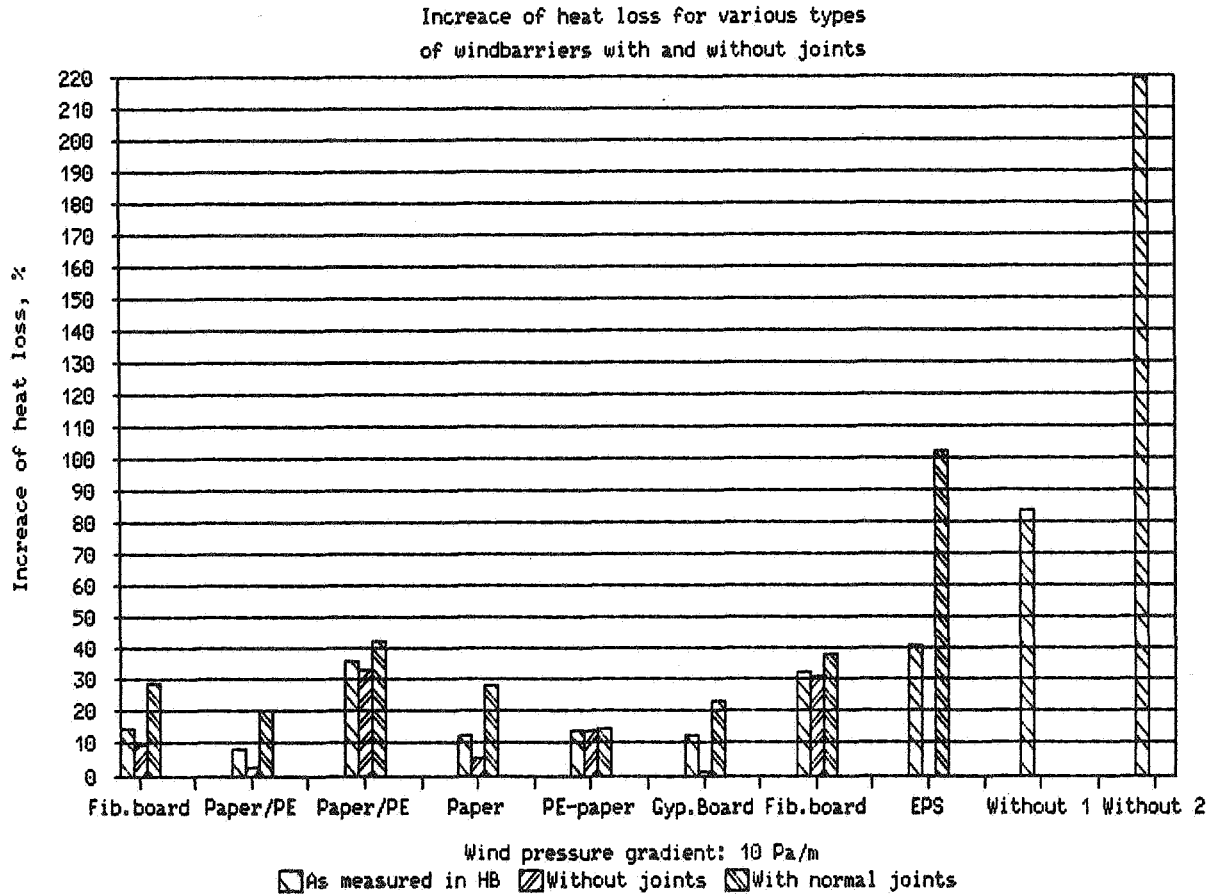


Diagram 8

Increase of heat loss through a wood frame wall insulated with 150 mm mineral wool protected with various types of wind barriers. Both measured and estimated values refer to a wind pressure gradient of 10 Pa/m along the wind barrier. See text for further explanation.

The diagrams shown apply to a particular house and construction details, but simplified estimates based on the diagrams and average wind speed may give good indication on the increase of heat loss during a heating season even for other houses.

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