INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
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# Air Infiltration Calculation Techniques An Applications Guide

AIVC

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This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

**Annex V** Air Infiltration and Ventilation Centre

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CONTENTS

## CHAPTER 3: Theoretical Methods



## CHAPTER 4: Subsidiary Calculations

CHAPTER 5: Algorithms and Worked Examples



CHAPTER 6: Data Reference

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

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The difference and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

## 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.

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## How To Use This Guide

The guide has been designed so that the material you need for your intended application is easily accessible. The flow chart in Figure 1 illustrates the structure.

Chapter 1 is a general introduction to the subject which outlines ventilation needs, strategies and options and then describes the essential components of air infiltration calculation techniques. Section 1.4 of Chapter 1 will help you decide which air infiltration calculation technique best suits your data needs. In general you will have to choose either an empirical measurement-based route, or a more fundamental theory-based technique.

Chapter 2 covers the empirical methods, and is complete in itself; you need no fundamental theory beyond that covered already in Chapter 1.

Chapter 3 deals with theory-based calculations, beginning with a formal description of air infiltration theory (section 3.1). This section sets out the fundamental concepts behind calculation techniques, since a clear understanding of these is essential in understanding the limitations of the various modelling methods. The numerical representation and the significance of the forces driving the process of air renewal is also described in detail.

Chapter 3 goes on to describe the different methods (section 3.2). The range of applicability and limitations of each model are outlined and the relevant choice of model for your application discussed. Here you will also find a description of the role of flow modelling in predicting air distribution patterns. The data requirements for the models are spelt out in section 3.3.

Chapter 4 deals with subsidiary calculations using the air infiltration results obtained through either Chapter 2 or Chapter 3. The calculations cover ventilation and air infiltration heat loss, heat recovery, cost-effectiveness and indoor air quality.

Chapter 5 is devoted to algorithms and worked examples/case studies. The algorithms outlined there have been published in the literature and are freely available in the form of annotated computer listings. The worked examples are chosen to illustrate the various techniques available and the assumptions necessary to perform numerical calculations.

The final chapter is for reference. It contains a compilation of the available data suitable for use in design calculations; it covers climatic data, air leakage information and wind pressure data.

A glossary of terms is included at the end.

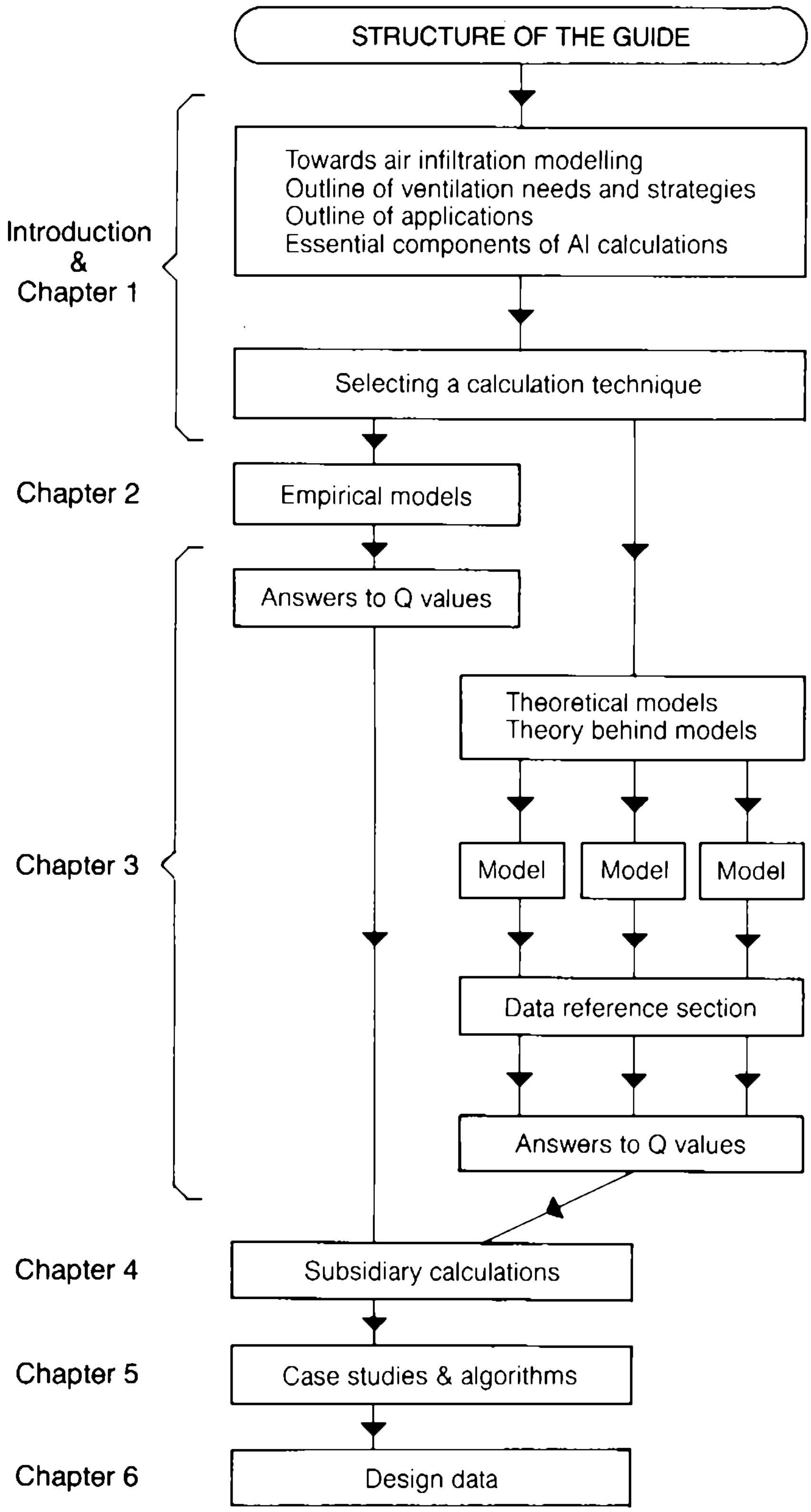



Figure 1 Structure of Guide

## INTRODUCTION

Air infiltration and ventilation has a profound influence on both the internal environment and on the energy needs of buildings. Inadequate attention to ventilation may result in an unacceptable indoor climate which, under extreme conditions, can be harmful to occupants. On the other hand, unnecessarily high air change rates will present an excessive burden on the building's heating (or cooling) system, resulting either in an unnecessary waste of energy or in the inability of the heating or airconditioning system to satisfy thermal requirements. Problems relating to moisture migration, cold draughts and a generally uncomfortable living or working environment may also be experienced. This subject has therefore become a key factor in both energy conservation and indoor air quality studies.

Air exchange in buildings occurs as a consequence of natural air infiltration and through the use of purpose provided ventilation. The former mechanism is the uncontrolled flow of air through penetrations in the building fabric caused by pressure differences generated across these openings by the action of wind and temperature. As such it is a very haphazard approach to ventilation which cannot be relied upon to provide a steady supply of fresh air. It also provides little control over the pattern of air movement within buildings. Air exchange induced by purpose-provided ventilation is intended to satisfy fresh air requirements in buildings with the minimum of external influence. By good design it may be used to control air distribution and to provide the basis for heat recovery from extract air.

Although air infiltration suffers from many disadvantages, this process, coupled with the use of openable windows, vents and stacks, continues to play a dominant role in meeting the ventilation needs for many varieties of building in a large number of countries. However, the problems associated with widely varying air change rates, poor control and uncertain air distribution, have become important considerations in both modern building design and in the upgrading of existing buildings. Although purpose-provided mechanical ventilation systems can overcome these problems, the benefits provided by such methods may easily be destroyed by inadequate attention to the interaction of intentional ventilation with that caused by air infiltration. Thus a poorly implemented ventilation strategy, combined with an inappropriately designed building shell, may adversely affect both energy needs and indoor climate. Poor design may also be expected to affect the reactions of occupants, especially in relation to window opening behaviour.

Despite the importance of the process of air infiltration, it is still an aspect of building physics about which there is considerable uncertainty. In part, this problem has been made difficult by the diverse range of buildings, each constructed according to widely varying specifications and site practices. In the past, progress has also been hampered by the inherent difficulty of actually making measurements which, in turn, has resulted in a wholly inadequate database for use in the development of predictive techniques. Furthermore, the complexities of the flow mechanisms themselves have added to the difficulty of quantifying infiltration rates. It is this lack of understanding which has frequently resulted in deficiences in design. Often airtightness measures are misunderstood and are applied without due consideration to ventilation needs or ventilation approach. The outcome may be reflected in moisture problems, severe contamination of the indoor air and possibly backdraughting from flues and exhaust vents. Clearly, good design will minimise the problem, yet without explicit guidance there is little that can be accomplished to improve design methods.

From the point of view of design, the principal task is to minimise energy consumption by reducing air infiltration while maintaining good indoor air quality. To achieve this design objective, it is necessary to provide guidance on the optimum conditions for either natural or mechanical ventilation, particularly in relation to the airtightness of the building shell and to climatic parameters. It is equally important to provide information on calculating the cost effectiveness of alternate ventilation strategies and to illustrate the importance of each approach in relation to minimising indoor air quality problems.

Recently, advances in both experimental techniques and mathematical modelling approaches have resulted in a considerable improvement in the understanding of air infiltration. The use of tracer gas as a direct measure of air infiltration and ventilation rates has been developed to the point where measurements are relatively straightforward to perform while, in some countries, the pressurisation test for measuring the airtightness and air leakage characteristics of the building shell is becoming routine and, in some instances, is mandatory. Furthermore, measurement methods that were once only suitable for small single family dwellings have now been adapted to suit the needs of large industrial and commercial buildings. Unfortunately, however, measurement methods suffer from a number of drawbacks. In particular, the tracer gas technique requires many discrete measurements to be made over an extended period of time to determine the long-term weather-dependent infiltration behaviour of a building. Also, measurement methods are of little direct value in the design process, since they can only be used to assess the performance of existing structures. However, by combining the results of many measurements, a general pattern of air change relationships emerges. Additionally, by using the data to verify the performance of numerical calculation techniques it has become possible to develop very powerful predictive methods. As a consequence, mathematical methods are now capable of playing a fundamental role in the design and evaluation of energy ventilation strategies. By combining the design air leakage and ventilation parameters of a building with local terrain and climatic data, mathematical models provide an alternative route to the estimation of air change rates (see Figure 2).

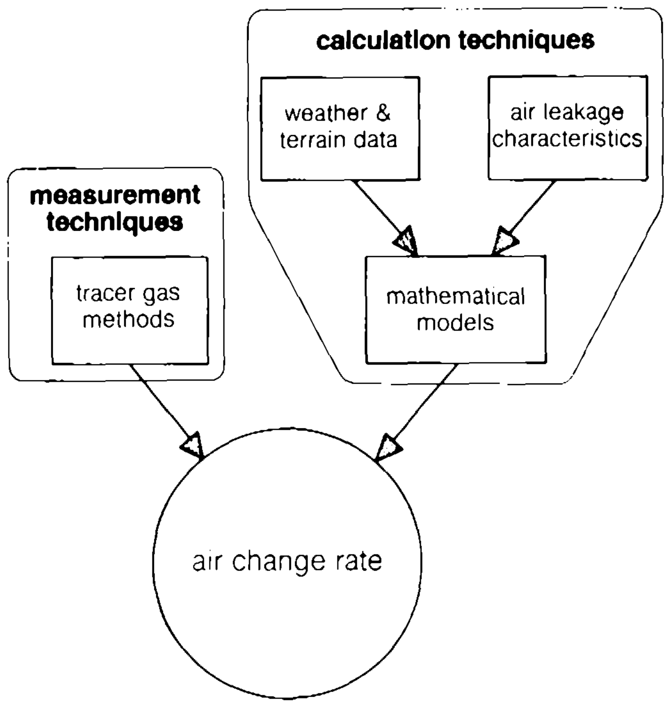



Figure 2 Alternative routes to the estimation of air change rates

The intention of this publication is to provide both researchers and designers with detailed background to air infiltration modelling and to give step-by-step guidance on the application of modelling techniques in design. Particular emphasis is devoted to providing specific guidelines on the calculation of steady-state air infiltration and on air change rates in industrial, commercial and domestic buildings. Associated calculations include the determination of infiltration heating and cooling loads, air flow and internal pressure distribution, the prediction of pollutant concentrations in buildings and an analysis of cost effective ventilation strategies. In addition to providing these guidelines, the rationale behind each calculation technique is described in full. Since the approach to ventilation strategy varies considerably on a national basis (largely as a result of climatic differences), the varying needs of each country are also discussed.

This guide is presented in loose leaf format to enable fresh examples, country data and new concepts to be readily accommodated.

## CHAPTER 1: Scope of Applications and Techniques

CHAPTER 1: Scope of Applications and Techniques

## INTRODUCTION

Mathematical models provide an inexpensive and rapid method for analysing an almost infinite variety of ventilation design options. They also have applications in air infiltration and in indoor air quality calculations. Their value extends to ventilation design applications in virtually all varieties of building, either at the design stage of a new building or as part of a planned refurbishment programme.

The strengths of infiltration models as an aid to ventilation design are summarised in Figure 1.1. Fixed conditions, including climate, shielding and terrain information are combined with design details as input data. Models are then used to predict corresponding air change rates, flow patterns, energy requirements and cost benefits. Variables over which the designer has control can then be optimised to best suit his requirements.

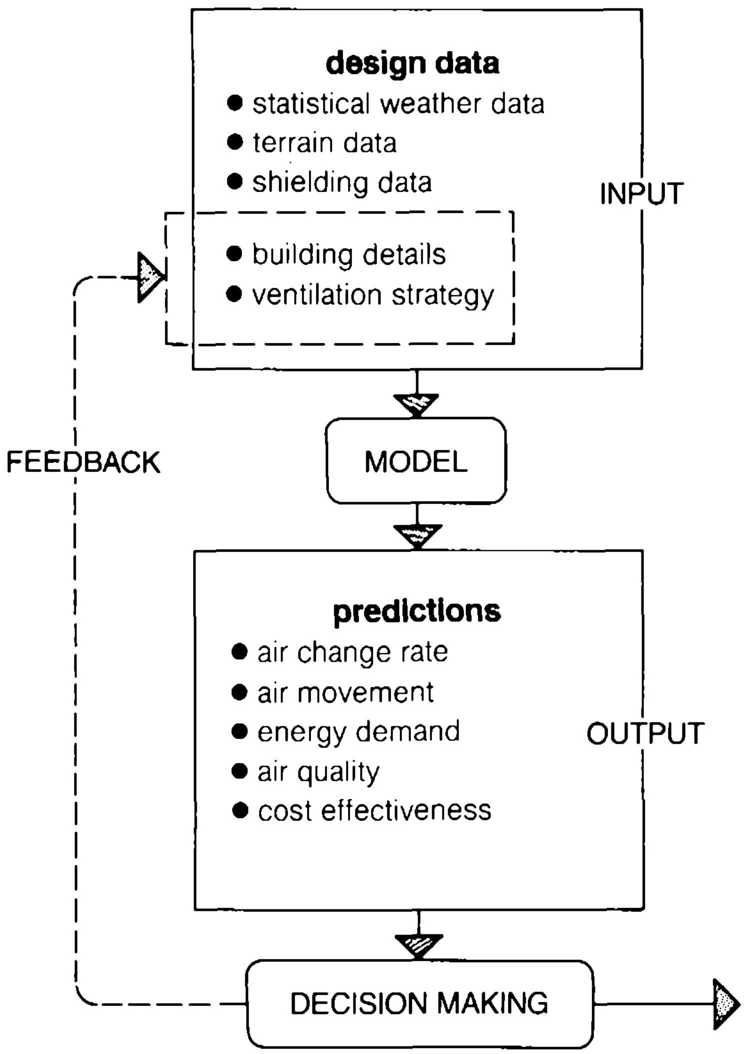



Figure 1.1 Role of mathematical modelling in design

This chapter covers the necessary material for you to select an appropriate model for your chosen application. The first two sections examine some of the basic facts about ventilation needs, strategies and options. The next section, 1.3, looks at the essential elements of air infiltration models and describes the kind of information that can be obtained simply by studying these elements. The final section aims to help you match a model with your application requirements.

After reading this section you ought to be able to assess whether you can obtain the information you need by a simple non-theoretical route (covered in Chapter 2), or if you require the greater rigour and accuracy of the theoretical techniques, which are dealt with in Chapter 3.

## 1.1 VENTILATION NEEDS AND STRATEGIES

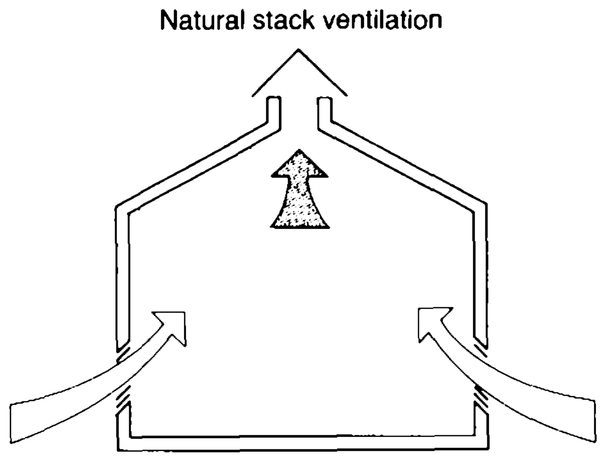
### 1.1.1 Industrial Buildings

Industrial buildings are characterised by large single zone structures which are used for manufacturing or storage. In buildings subjected to energy-intensive processes, ventilation is essential for cooling purposes. Summertime heat gains can also be considerable with the result that the prime ventilation objective is again to remove excess heat. In addition to the need to meet general ventilation requirements, smoke and pollution control may be expected to impose an overriding demand on ventilation approach.

Depending on climate and/or the quantity of internally generated heat, heat gain may be dissipated using either mechanical extract or natural ventilation (see section 1.2). In the case of extract ventilation, the fans are mounted at roof level where the warm air collects while, for natural ventilation, a combination of roof and low mounted wall vents is used to promote stack action. The mechanical approach may also require a complementary supply air distribution system to satisfy make-up air needs and to ensure adequate comfort conditions. An alternative method of satisfying general ventilation needs is to use a mechanical supply system, which maintains an overall over-pressure within the building and minimises the risk of contamination. Typical examples of ventilation are illustrated in Figure 1.2.

For buildings subjected to light manufacturing processes or storage, the wintertime ventilation objective will be altogether very different to that of the summer months. Insufficient attention to airtightness will result in considerable infiltration heat loss, while the operation of loading bay doors will further add to heat loss and to general discomfort. Even in buildings subjected to excessive process heat, energy reductions are feasible by minimising ventilation rates outside operational periods.

Energy efficient ventilation design must therefore take into consideration the need to both maximise ventilation (in order to dissipate solar and process heat gains), and to minimise ventilation when these special conditions no longer apply . The design calculation techniques presented later in this guide are applicable to both requirements.



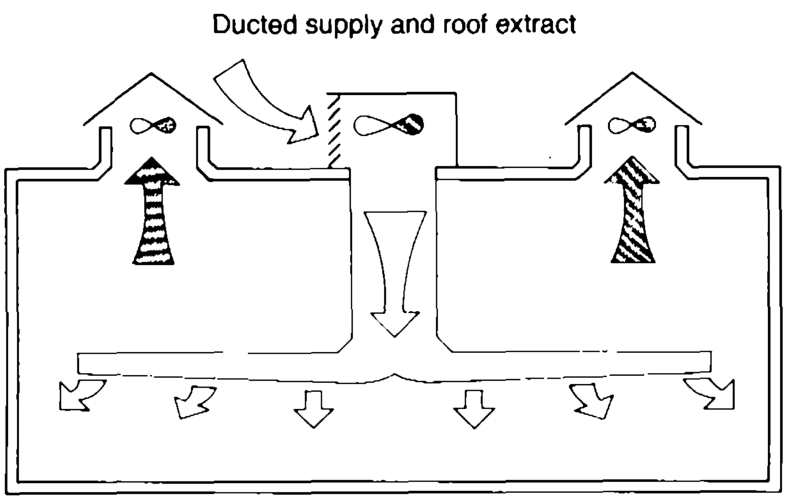




Figure 1.2 Industrial ventilation

### 1.1.2 Commercial Buildings

In terms of size, age, airtightness and ventilation approach, commercial buildings are subject to an extremely diverse range of conditions.

Apart from climatic considerations, air handling systems are needed to circulate air in large office buildings, while mechanical ventilation is often desirable in city centre locations to minimise the intrusion of outside noise through open windows.

In relation to energy efficiency, good ventilation design, coupled with attention to building airtightness, presents an ideal opportunity to recover waste heat from lighting, office equipment and occupants. In many instances this can prove to be a very attractive proposition. On the other hand, care in design is essential to prevent indoor air quality problems.

### 1.1.3 Dwellings

With regard to airtightness, dwellings represent the most widely studied variety of building. In many countries a good picture of the airtightness performance and air infiltration characteristics of both single-family and apartment buildings is emerging. The majority of current measurement techniques were originally developed for housing since the relatively small unit size of dwellings in comparison to other buildings has provided the best opportunity for monitoring and verification. From the design point of view, it is possible to construct a dwelling to accurate airtightness tolerances[1]; the principle task therefore is to determine the most appropriate combination of airtightness and ventilation strategy to provide cost-effective ventilation performance.

Mathematical models for dwellings are well established and several of these models formed the focus of an AIVC programme to validate the performance of air infiltration prediction methods[2]. Most models are capable of simulating the various conditions to be found in dwellings.

## 1.2 VENTILATION OPTIONS

### 1.2.1 Natural Ventilation

Natural ventilation remains a common method for satisfying fresh air requirements in buildings throughout many parts of the world. In its most basic form, needs are met by adventitious air flow supplemented by the use of openable windows and vents. In addition, air bricks and other forms of fixed air vents are sometimes a mandatory requirement, especially where open fireplaces and unvented appliances are in use. In some countries, natural ventilation stacks are required to enhance ventilation and improve air distribution, especially in high-rise buildings. Inclusion of the effects of purpose-provided openings may be readily incorporated into infiltration models (section 3.1.1).

A disadvantage of natural ventilation is the inherent difficulty in controlling the rate of air change, since this is dependent on the variable nature of wind and temperature. In mild climates, this problem can often be kept within acceptable tolerances by careful attention to building airtightness, the provision of purpose-provided ventilation openings and the training of occupants. In severe climatic regions such control may become more difficult and in such areas mechanical ventilation systems have become popular.

### 1.2.2 Mechanical Extract (or Supply) Ventilation

The mechanical extraction of air creates an internal underpressure which draws supply air through adventitious and/or purpose-provided openings in the building envelope.

Provided this negative pressure is maintained against the actions of wind and stack pressure, the rate of air change is dominated by the ventilation system. In theory it is possible to make a building sufficiently airtight and to develop sufficient underpressures to prevent weather influences entirely. However, such an action may result in serious indoor air quality problems. Even for relatively low underpressures, problems associated with high velocity draughts and back draughting can occur (see Section 4.3.1). The mechanism by which this ventilation approach dominates the air change rate is illustrated in Figure 1.3. In Figure 1.3(a), a substantial underpressure is developed and air enters the building through all surfaces. As wind speed increases, the pressure on the leeward side of the building eventually equals that of the internal air pressure and air ceases to enter through this face (Figure 1.3(b)). For further increases in wind speed, the internal pressure becomes positive with respect to the leeward side and the influence of climate begins to take effect (Figure 1.3(c)).

In addition to providing good control over the ventilation rate, mechanical extract ventilation provides the opportunity for heat recovery from the exhaust air using a heat pump (Section 4.1). This has become a popular option in some countries especially in apartment buildings. However, sometimes mechanical ventilation is unsuitable since it can promote the transfer of external sources of pollution through the building shell. This is a particular problem in instances where urea formaldehyde has been used as thermal insulation or in locations where radon can enter the building from underlying strata. Excessive underpressures can also lead to backdraughting from flues (Section 4.3.1).

The converse approach of supply-only ventilation presents a similar opportunity for ventilation control but not for heat recovery. This method of ventilation is not a popular choice for many buildings since a pressurised building is likely to encourage internally-polluted moist air to enter the fabric of the building where it may subsequently condense. If, for special applications, supply-only ventilation is necessary (for example industrial applications (Section 1.1.1)), a similar mathematical analysis to that suitable for mechanical extract ventilation will normally apply.

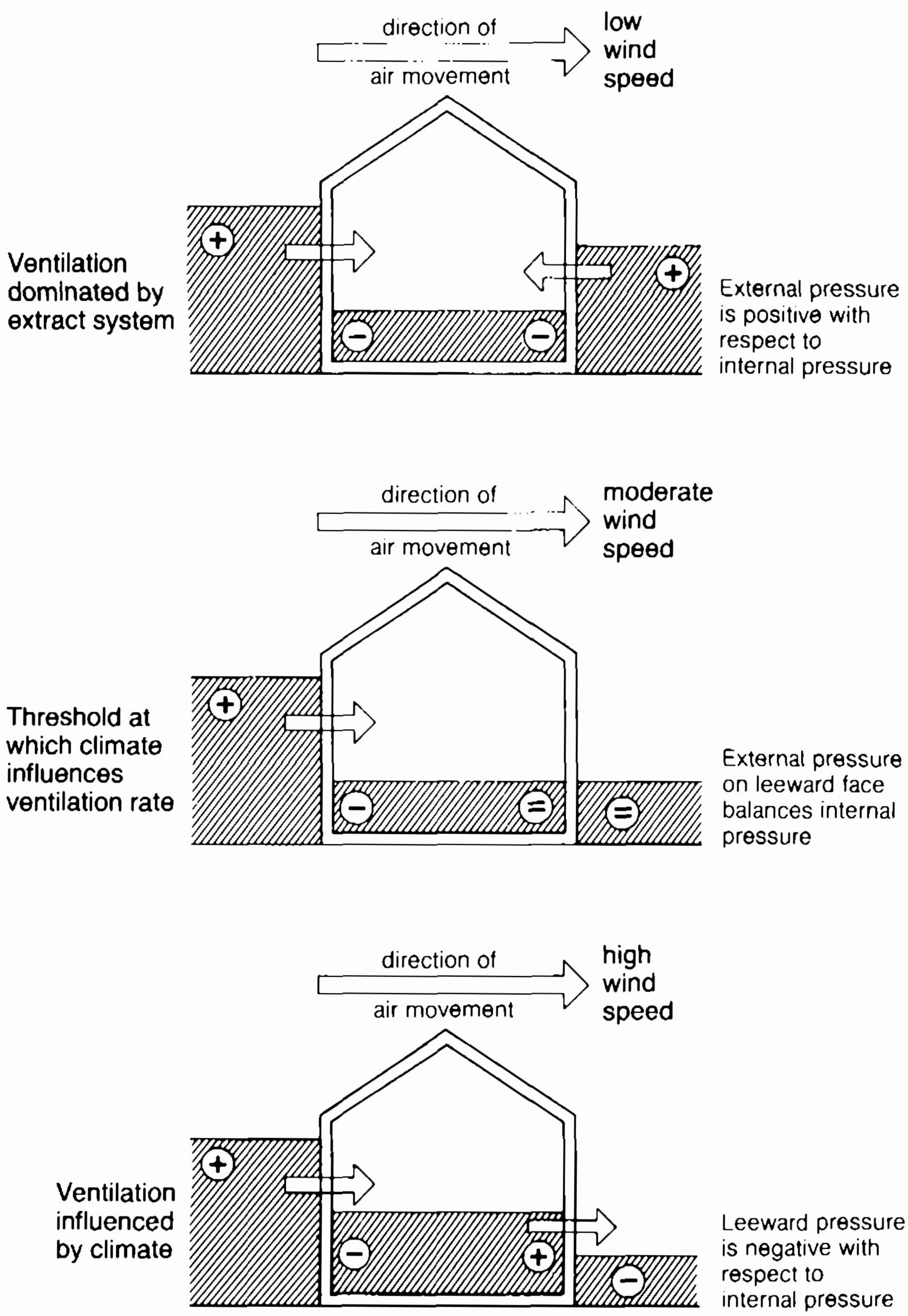



Figure 1.3 Influence of wind infiltration on extract ventilation

### 1.2.3 Balanced Supply/Extract Systems

This differs from the extract-only system in that a separate mechanical supply network is introduced to replenish extracted air. Balanced systems provide the opportunity for air-to-air heat recovery (Section 4.1) and also permit good control over the movement of air within the building. However, since supply air is provided by mechanical means, a completely balanced system will not alter the overall pressure balance within the building. Therefore the system offers no resistance to the effects of wind and stack induced air infiltration. It is for this reason that background leakage and other unintentional openings must be reduced to an absolute minimum. Some allowance for adventitious leakage is normally made by introducing a slight imbalance in the supply/extract rates in favour of extraction (typically 10%). The resultant underpressure is also advantageous in controlling moisture migration and preventing interstitial condensation, although the potential for heat recovery is correspondingly reduced.

## 1.3 TOWARDS AIR INFILTRATION MODELLING

The foremost task of an air infiltration model is to calculate the air change rate in a building for a given set of conditions. These basic conditions can be analysed in terms of the performance of the building in relation to both its airtightness and its proximity to other obstructions (air infiltration characteristics), seasonal and climatic influences, and terrain factors. These parameters combine to fix the infiltration behaviour of a given design approach and therefore their accurate interpretation forms an essential first step in any applications study. Hence, before progressing to other design considerations, the scope of basic infiltration calculations is considered.

### 1.3.1 Air Infiltration Characteristics

Three primary aspects affect air infiltration:

- the overall airtightness of the building
- the climatic influence behind the driving mechanism
- the topographic environment in which the building is located

These parameters uniquely define the air infiltration characteristics of individual buildings and can be readily represented in graphical form (see Figure 1.4).

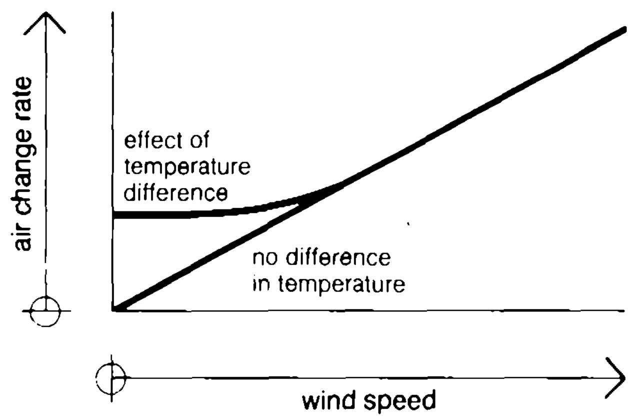



Figure 1.4 Infiltration characteristics

The curves are constructed by using a numerical model to calculate the rate of air infiltration for fixed increments in wind speed and temperature, covering the climatic range for the locality (see Section 6.1). This approach provides an invaluable aid to the visualisation of air infiltration performance for specific design conditions. By constructing such curves for different topographic conditions, it is also possible to analyse the influence of shielding on air infiltration rates. In addition this approach enables an approximate indication of air change rates to be determined for a wide range of wind and temperature conditions without further recourse to a mathematical model.

### 1.3.2 Seasonal and Climatic Variations in Air Infiltration Rates

In practice it is inevitable that certain combinations of wind and temperature will result in either too much or too little infiltration. It is therefore often necessary to take the calculation of rates of air infiltration a stage further in the design process by determining the frequency of occurences or time intervals for which unsuitable conditions prevail. This is possible using statistical climatic data relating hourly mean wind speed with air temperature to produce hour-by-hour frequency distributions of air infiltration (Chapter 6.1). Typical results are illustrated in the form of a histogram and an accumulative frequency plot in Figures (1.5(a) and 1.5(b) respectively. Figure 1.5(a) also illustrates how climatic severity influences the distribution of air change rates.

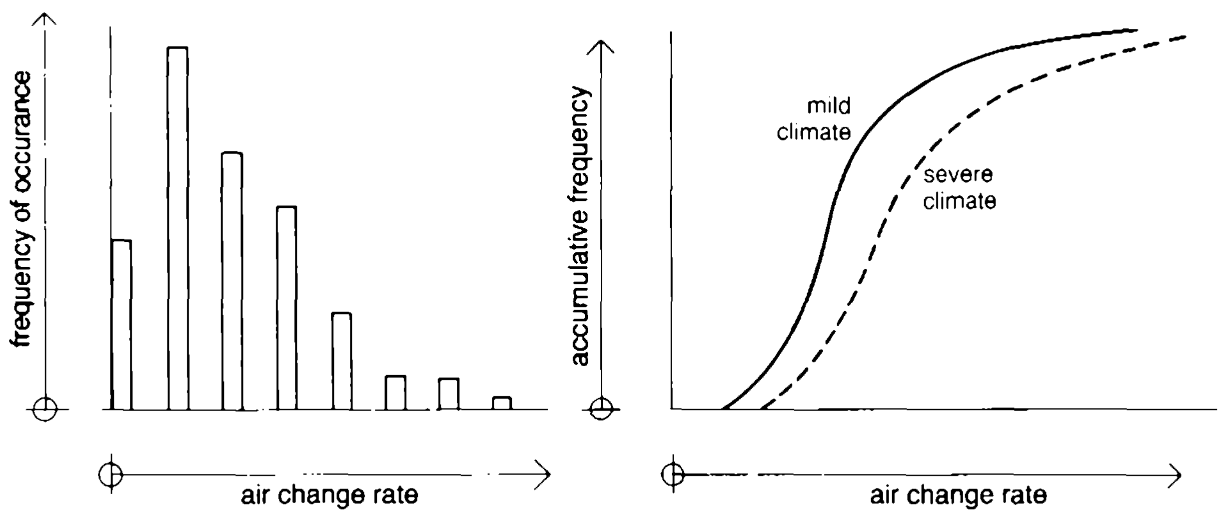



Figure 1.5 Distribution of infiltration rates throughout a heating season

These results may be used to analyse the potential energy losses associated with natural ventilation strategies or to investigate the need for controlled ventilation in instances where a building is too airtight to support natural ventilation.

### 1.3.3 Terrain and Shielding Effects on Air Infiltration

Both terrain and local shielding affect the influence of wind and air infiltration. Typically wind data are obtained from the nearest meteorological station to the site of the building and are presented in the form of wind speed at a height of 10m in open flat country. Terrain and shielding corrections are essential (Section 3.1.3.1) and have a dramatic effect on air change as illustrated in Figure 1.6.

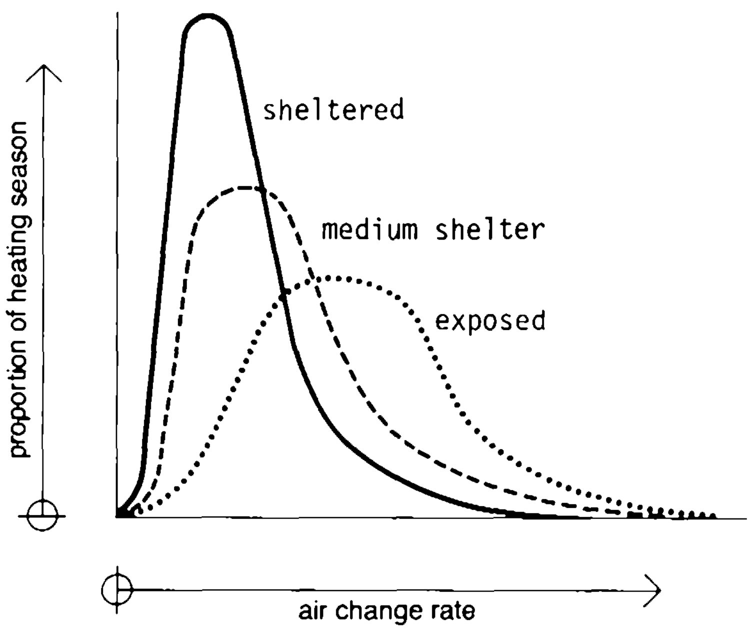



Figure 1.6 Influence of shelter on infiltration rate distribution

Thus, for a given meteorological wind speed, local values will vary according to the environment. Therefore buildings displaying identical air leakage performance will not necessarily experience the same infiltration rates when subjected to similar weather conditions. This is an important consideration in prediction methods.

### 1.3.4 Distribution and Size of Openings

For a fixed level of building airtightness, it is possible for air infiltration rates to be considerably affected by the manner in which openings are distributed. For example, openings located on a single side of a structure will minimise the effect of wind-motivated air infiltration because there is no path through which air entering the building can escape. This is particularly true if the openings are also located at a single height, such that the influence of stack effect is also minimised. Under these circumstances, turbulent fluctuations can become an important driving mechanism (see Section 3.1.3.2). Large single-sided openings such as factory entrances also need special attention to ensure that the simultaneous flow of air in both directions through the entrance may be correctly simulated (Section 3.4.1.3). Problems relating to the uneven distribution of leakage openings can generally be predicted with most air infiltration models, and, indeed, the distribution and size of openings normally forms a key data requirement. It is therefore possible to use air infiltration modelling techniques to assess the significance of leakage distribution. This is especially useful, for example, in optimising the location of purpose-provided openings or in analysing the influence of wind direction on air infiltration. Typical examples highlighting the effect of leakage distribution on air infiltration rates are covered in Section 5.2 as worked examples.

### 1.3.5 Purpose-Provided Ventilation

It is not normally possible to isolate air infiltration from purpose-provided ventilation. This is because identical flow mechanisms apply and hence inseparable interaction occurs between adventitious and intentional flow. In many ways, purpose-provided ventilation presents a much more straightforward problem for models to deal with than infiltration itself, since the size, flow characteristics, and location of supply and extract openings all form part of the design option. Much greater certainty over the flow behaviour within a building is possible, provided that careful attention is devoted to minimising background leakage. Such an approach leaves the designer with considerably greater flexibility in providing adequate ventilation than is possible by relying on the haphazard nature of adventitious ventilation.

## 1.4 NUMERICAL METHODS

The intention of this section is to direct you to the most appropriate calculation technique for a given application. Guidance is presented on the choice of calculation method, requirements for multi-zone or single zone methods and the selection of techniques according to application.

Having selected the most appropriate application and calculation technique, you can locate the relevant sections of the design guide to obtain further information on how to proceed.

### 1.4.1 Calculation Techniques

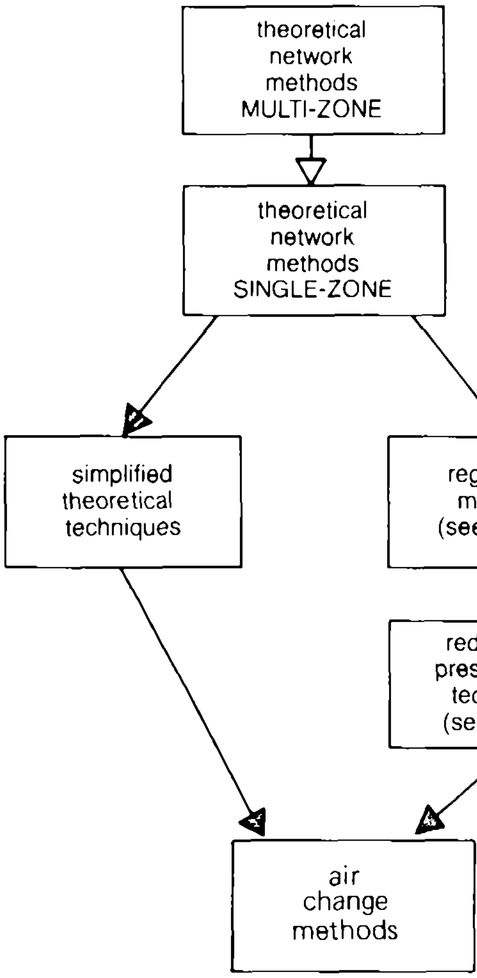
There are essentially five generic forms of calculation technique available for air infiltration and ventilation predictions. These are:

1. "Air change" methods
2. Reduction of pressurisation test data
3. Regression techniques
4. Theoretical network methods
5. Simplified theoretical methods

It is from this list that the choice of method will be selected. Methods 1-3 are empirical techniques and are dealt with in Chapter 2. Chapter 3 covers the other two methods, which are based on a more fundamental approach. A summary of the different techniques is presented in Table 1.1.

### 1.4.2 Hierarchical Order of Techniques

The various forms of calculation technique have a hierarchical order representing both their range of applicability and their level of complexity (Figure 1.7).




Notes:

1 Assumes that air infiltration rates can be measured in the building.

2 Assumes that airtightness measurements (pressurization testing) may be made or estimated.

Figure 1.7 Hierarchical order of techniques

Table 1.1 Summary of calculation techniques

(a) Empirical methods

| Technique | Data requirements | Availability of algorithms | Advantages | Disadvantages |
|---|---|---|---|---|
| Air change methods | Basic building design details (size, height, etc) | CIBSE and ASHRAE guides provide sufficient operational guidance | - Ease of use<br>- No computing facilities required | - Does not provide detailed infiltration predictions |
| Reduction of pressurisation test data | Pressuristion test data | None required | - Ease of use<br>- No computing facilities requires | - Applies only to existing buildings in which pressurisation test data is available<br>- Does not indicate the effects of weather, shielding and terrain conditions |
| Regression methods | Infiltration measurement data with corresponding wind and temperature records | ASHRAE Fundamentals | - Fairly easy to use. Regression coefficients may be calculated using the statistical functions on a pocket calculator.<br>- Gives weather dependent infiltration predictions.<br>- Can give reasonable results if care is taken to calculate regression coefficients. | - Only really applies to existing building in which tracer gas measurements have been made.<br>- Typical regression data are available but they can give very unreliable results. |

(b) Theoretical methods

| | | | | |
|---|---|---|---|---|
| Network Models | - Building description (size, dimensions, orientation, number of cells).<br>- Surrounding shielding data.<br>- Terrain roughness.<br>- Flow path data (location and description of leaks). | NBS Algorithms, also commercial algorithms are available. | - Predicts air distribution patterns.<br>- Determines internal pressure distribution.<br>- Responsible to weather, terrain and shielding parameters.<br>- Moderately sizeable networks can be run on small computers.<br>- May be used for combined air infiltration and mechanical ventilation calculations. | - Substantial data may be required to describe flow network.<br>- Considerable computational effort. |
| Simplified theoretical models | - Air leakage characteristics of building, eg pressurisation test data.<br>- Shielding data.<br>- Terrain roughness. | No specific algorithm has been published although sufficient details can be obtained from source papers. | Offers a compromise between the complexity of network models and the inaccuracy of empirical techniques | - Only applicable to single zone structures.<br>- Provides no information on the direction of air movement. |

As a general rule, alternative methods for specific applications can only be selected by moving up the hierarchy. Thus, by reference to Figure 1.7 a theoretical network method may be expected to fulfill the needs of all applications while "air change" methods are of much more limited value. On the other hand, network methods demand substantially more data than methods lower down the hierarchy (see Table 1.1).

### 1.4.3 Single/Multi-Zone Selection

A "single zone" or "single cell" building is one in which the interior air mass can be assumed to be well mixed and is at a single uniform pressure. Buildings which notionally conform to these conditions are dwellings, non-segmented industrial buildings and small open-plan commercial buildings.

A "multi-zone" or "multi-cell" building is one in which interior air flow is restricted by internal partitioning. Typical multi-zone buildings are apartment dwellings and large commercial buildings.

Whenever possible, it is preferable to use the single zone approximation since this considerably simplifies the calculation. Indeed if resources are limited or if insufficient data are available, then the single zone approach may prove to be the only viable method. Should a multi-zone representation prove to be necessary then the only satisfactory calculation technique currently available is the theoretical "network" approach.

The chart presented in Figure 1.8 is aimed at assisting the user in deciding whether or not the single zone approximation is permissible. The details below describe how to proceed down the chart.

Start — There are two possible starting blocks depending on the type of building under discussion. One start is for the notionally single zone building, while the other is for the notionally multi-zone building (multi-family dwellings and large commercial structures)

Distinct zones — This decision point looks to see if the ostensibly single zone building is in fact broken up, by design, into zones. An example of a dwelling that was not would be a single family house with warm air heating; an example of a dwelling which was would be a 3-storey apartment with a "wet" central heating system. If is is determined that the zones are distinct, the flow goes from the left column to the right one, otherwise it proceeds down the left column.

Well coupled — Even though there are recognisable zones in a structure, they may be so well coupled that they can be treated as a single zone. This decision must, in part, take into account the purpose, for example indoor air quality, but an example of good coupling might be a commercial building in which there is a single HVAC system that has both supply and return registers. If it is determined that the zones are well enough coupled, flow moves to the left column.

Well mixed

Although it may have been determined that any zones which exist are either well coupled or indistinct, the building may be poorly mixed. This is often true of large industrial type buildings such as warehouses, etc. If the mixing is poor, flow goes to the "ventilation efficiency" box. Alternatively, if the building is being treated as well coupled and well mixed, flow terminates at the "single zone model".

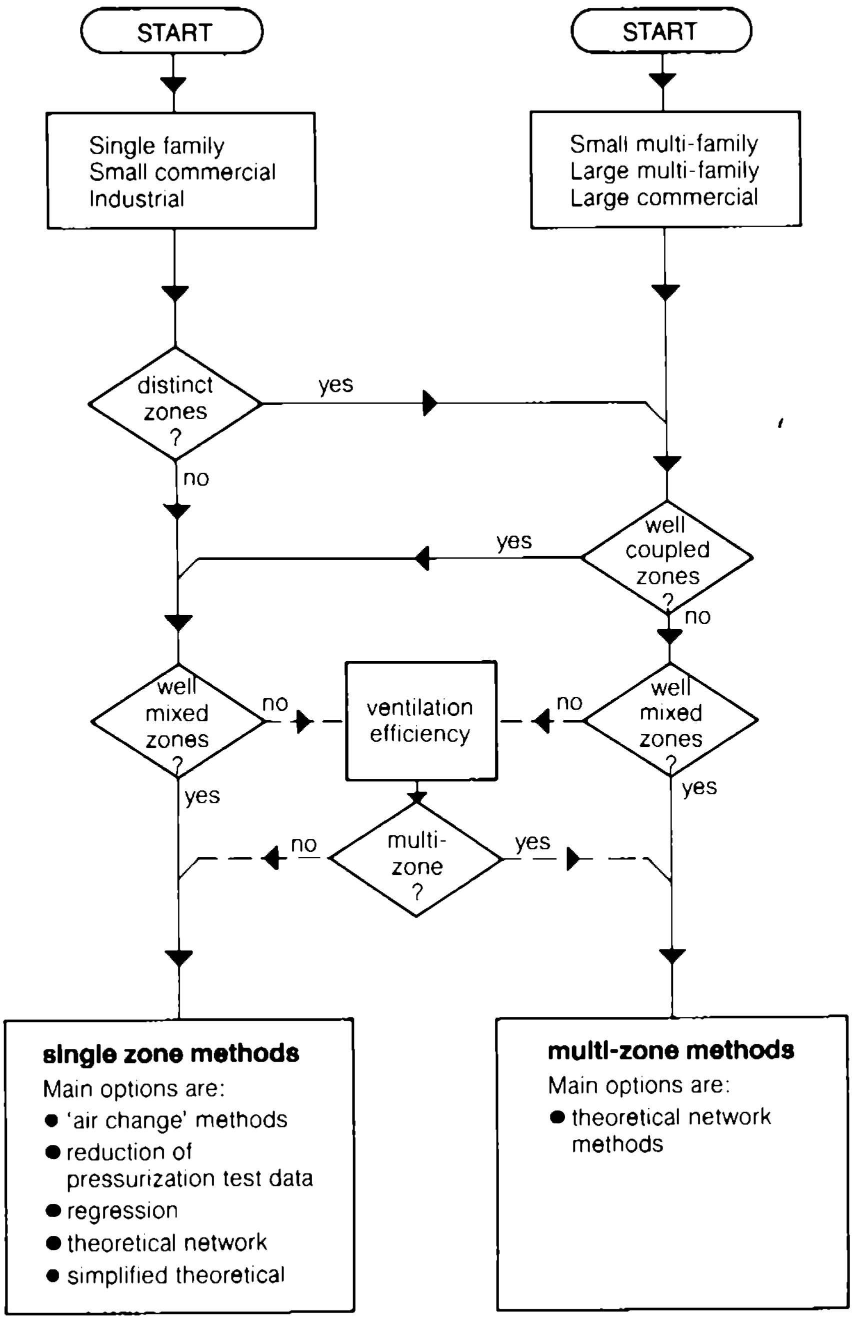



Figure 1.8 Single/multi zone selection

Vent. effic. This box denotes the fact that individual zones are poorly mixed and it is necessary to involve the concept of ventilation efficiency (Section 3.1.2). Unfortunately, there is no concensus on how to do this. Although research is underway, the user is left without appropriate algorithms and therefore must decide whether his purpose requires normal flow modelling or whether the ventilation efficiency issue can be ignored. As models develop, it may become possible to include ventilation efficiency in them.

In the end, the user will either end up at the single or multi-zone model box. This choice, combined with the application, will then lead to one of the model types.

### 1.4.4 Selecting a Calculation Technique

The applications covered by this guide and the initally recommended calculation approach for each are summarised in Figure 1.9. The process of selecting a suitable calculation technique begins by identifying the most relevant application from those listed in the figure. The recommended method is verified for sufficient accuracy and checked against data needs (Table 1.1). Should the choice of method prove to be unacceptable, then an alternative must be selected by moving up the hierarchical order of techniques (Figure 1.7). This process is continued until an acceptable method has been found. If a method proves unsuitable because of excessive data requirements, then you may have to refer back to the multi-zone/single zone decision chart (Figure 1.8) and further approximate your ideas so that a single zone approach may be used.

Finally, you can execute the calculation method recommended in the guide; or develop or modify an existing method using the information presented in Chapter 3 or seek specialist advice.

While every effort has been made to make the process as straightforward as possible, some of the decision points require you to understand the details and ramifications of the process being studied. In general, there is always a trade-off between accuracy, ease of use and data requirements. For example, a good multi-zone network approach can be used for any application; it can, however, have extensive data requirements and large networks require a high level of expertise and computer sophistication to run. Since the level of effort you have available may be an important consideration, the application chart (Figure 1.9) directs you to the simplest model for a given application.

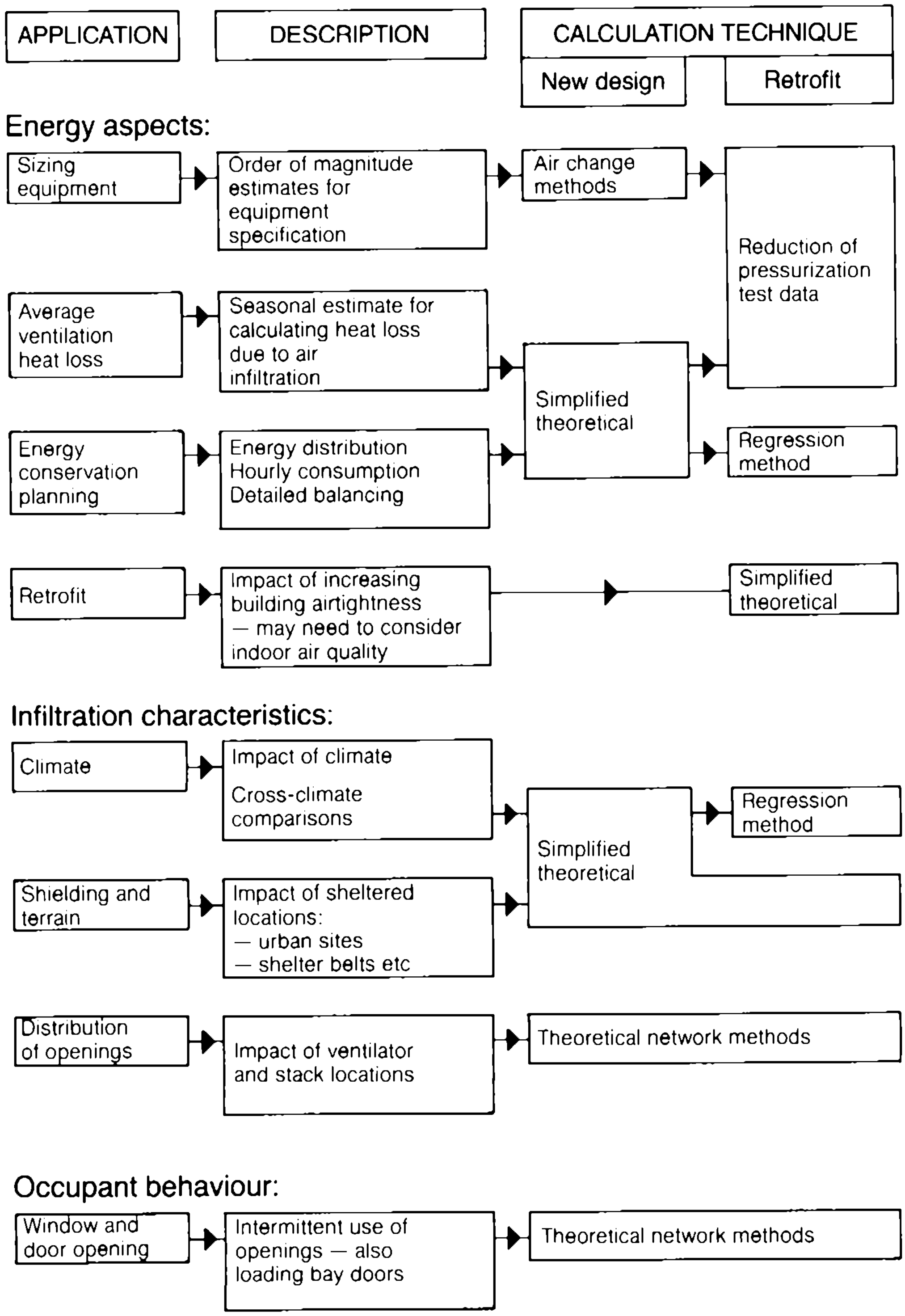



Figure 1.9 Selecting a calculation technique

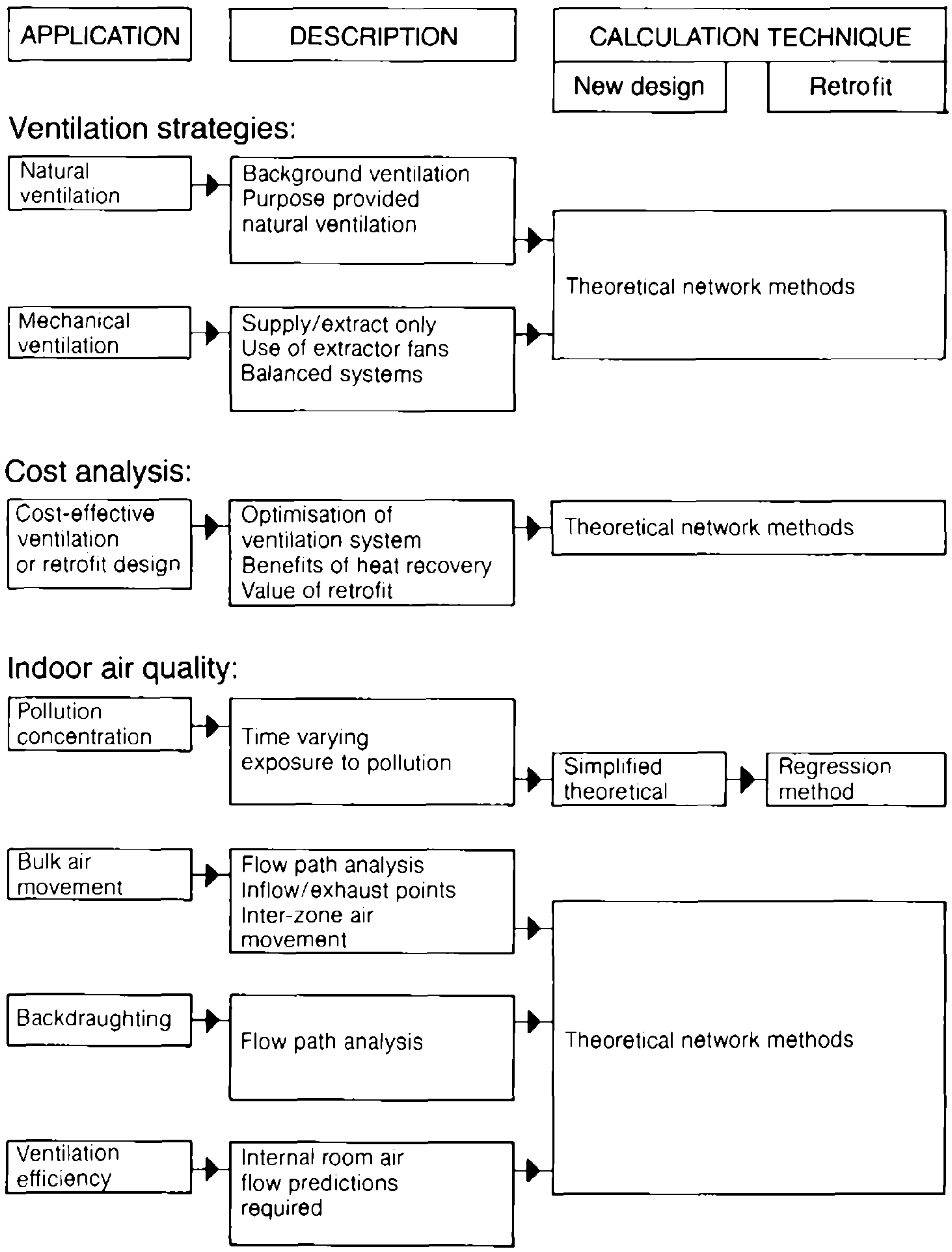



Figure 1.9 Selecting a calculation technique (continued)

Notes:

1 Mechanical ventilation
The air change rate in many buildings is dominated by mechanical ventilation. It is therefore important that any model used to represent such buildings should be able to take full account of these systems.

2 Occupants
Occupants can have a significant effect on infiltration by means of window and door opening. Window opening especially is used to control comfort conditions. In many instances the more rigorous calculation techniques are able to predict the effect of window and door opening. However, behavioural information, ie the motivation and conditions for window opening, is not so readily available. If windows are left open the overall effect on air change rate will often be considerable.

3 Subsidiary applications
This guide is primarily concerned with providing information on calculating air infiltration and ventilation rates. However, these values are not always the final answer as far as the user is concerned. Rather, they form a useful intermediate in reaching an objective. The most common step is to determine the heating or cooling load on the HVAC system of the building. Thus it is necessary to (a) calculate the energy content of the ventilation and (b) combine it with other whole building factors to determine the load.

Indoor air quality is another important issue; it uses ventilation to determine the concentration of specific pollutants and, hence, a total occupant exposure. Ventilation efficiency issues are also becoming of greater importance. Such indoor air quality issues can be combined with energy calculations and cost data in an integrated approach to find the system which delivers adequate comfort and safety to minimum life cycle cost.

Common subsidiary calculation techniques can be found in Chapter 4.

**REFERENCES**

1 Elmroth, A and Levin, P
Air infiltration control in housing - a guide to international practice.
Swedish Council for Building Research, DA:1983.

2 Liddament, M and Allen, C
The validation and comparison of mathematical models of air infiltration.
Technical Note AIC-TN-11-83, Air Infiltration Centre, Sept 1983.

# CHAPTER 2: Empirical Techniques

infiltration rate is calculated based on design wind speed. Adjustments are then made to individual room rates according to window distribution and room level. The second approach makes use of a table of expected values for buildings of typical construction.

### 2.1.2 Reduction of Pressurisation Test Data

This is a very simple technique which nevertheless provides valuable information concerning the average infiltration performance of a building. The artificial pressurisation or depressurisation of a building as a means of assessing air leakage performance is now a fairly common practice[3]. In itself it only provides data regarding the "leakiness" of the building (usually expressed in terms of air change rate at a 50 Pa pressure difference, $Q_{50}$). The result provides no information on the distribution of openings or on how infiltration will be affected by wind, temperature, terrain, or shielding. However, numerous experimental tests have shown that the approximate air infiltration rate will be of the order of one twentieth of the measured air change rate at 50 Pa, ie:

$$Q_{inf} = Q_{50}/20 \qquad (h^{-1}) \qquad (2.1)$$

where $Q_{inf}$ = infiltration rate ($h^{-1}$)

$Q_{50}$ = air change rate at 50 Pa

This provides a useful "rule of thumb" estimate should pressurisation test data be available. It is of value when considering the implications of building airtightness on the design performance of either natural or mechanical ventilation strategies. For example, a naturally ventilated building intended to meet an average ventilation requirment of 0.5 air changes/hour (ach) would require an overall air leakage rate at 50 Pa of not less than 10 ach. Similarly a mechanically ventilated building would need a considerably greater degree of airtightness if interference by air infiltration is to be avoided. The method is, however, only suitable for small buildings such as dwellings, in which the pressurisation test can be made.

### 2.1.3 Regression Techniques

This method is based on the results of statistical fits to long-term time series data of infiltration rate measurements and associated climatic data. In its most basic form air infiltration is expressed as a linear function of wind and temperature, ie:

$$Q_{inf} = a' + b'\Delta T + c'V^2 \quad (h^{-1}) \qquad (2.2)$$

where $Q_{inf}$ = infiltration rate ($h^{-1}$)

$\Delta T$ = internal/external temperature difference ($^{o}C$)

$V$ = wind speed (m/s)

$a', b', c'$ = regression coefficients

Known combinations of $\Delta T$ and V are substituted into the above equation and the regression coefficients are calculated by the method of least squares.

The main value of this approach is in the extrapolation of results beyond a measurement period. Typically, hourly rates of air infiltration are continuously measured over a period of a few days. Appropriate regression coefficients are then evaluated and the performance of the infiltration equation is verified over a further short measurement period. The regression equation may then be used to estimate air infiltration performance of the building over a wider set of climatic conditions.

The main disadvantage of this method is that the calculated regression coefficients are unique to the building since they reflect not only the airtightness performance of the building but also its orientation with respect to adjacent obstructions. It is therefore not possible to transfer the data to other buildings. Although representative values of regression coefficients have been published for design purposes, they can be very unreliable.

**References**


1 CIBSE Guide A4 Infiltration
The Chartered Institution of Building Services Engineers, 1976

2 ASHRAE Fundamentals, Chapter 22, American Society of Heating and Refigerating and Air Conditioning Engineers, Inc, 1985.

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Techniques and Instrumentation for the Measurement of Air Infiltration in Buildings - a Brief Review and Bibliography.

CHAPTER 3: Theoretical Methods

## CHAPTER 3: Theoretical Models

### INTRODUCTION

The severe restrictions imposed by empirical regression techniques limit detailed design calculations to a full solution of the theoretical flow equations outlined in Section 3.1.1. Such models take the form of a flow network in which nodes representing regions of differing pressure are interconnected by leakage paths. This network is described by a set of simultaneous equations formed by applying the desired flow equation (equations 3.1 - 3.5) to each of the paths. These equations are then solved by determining an internal pressure distribution such that a mass flow balance is preserved between the infiltrating and exfiltrating air masses.

Theoretical models of varying degrees of complexity are available and it is important therefore to make the correct selection according to both building type and intended application. The simplest of all network models approximates the interior of a building as a single zone at uniform pressure. This approximation is generally satisfactory for industrial-type buildings such as factories and warehouses and for calculating the overall air change rate in dwellings. However, where partitioning presents an impedence to the general movement of air, it is necessary to divide the interior of the building into discrete zones with interconnecting flow paths. Such an approach is almost always necessary in commercial and multi-storey buildings in which floor space is partitioned into office accommodation or in which individual floors are connected by lift shafts and stairways. The latter approach is normally also necessary for air movement and indoor air quality design predictions in dwellings.

Section 3.1 describes the necessary theoretical considerations behind all the models. In 3.2 the various theoretical modelling techniques are described in detail and their respective advantages and disadvantages are discussed. The remainder of the chapter is devoted to the data requirements of models.

### 3.1 THEORETICAL BACKGROUND

Air infiltration is primarily governed by building airtightness and the magnitude of pressure imbalances developed across envelope penetrations. It is also influenced by the distribution of leakage paths, the flow characteristics of individual openings and internal impedences to air movement. A fundamental concept behind the processes of air infiltration and ventilation is that air entering the building displaces an equivalent mass of internal air, ie a mass flow balance is maintained. This section is devoted to presenting a theoretical background to the mathematical representation of the air infiltration process with particular emphasis on the driving forces behind air infiltration and the nature of flow through openings. A thorough understanding of this background material and their numerical approximations is essential if results are to be successfully interpreted.

### 3.1.1 Flow Mechanisms

The mathematical representation of air flow through cracks and openings is extremely complex. This is especially so when dealing with air infiltration since each penetration of the building fabric is unique. It would be a formidable task to identify and incorporate into a mathematical model the flow properties of every opening. Consequently, it is necessary to make a number of simplifying assumptions which retain the main physical concepts but enable an acceptable mathematical interpretation of the flow process to be formulated. It is the degree to which the flow mechanics is simplified that identifies models and governs their data needs and overall range of applicability.

For a given applied pressure, the nature of air flow is dependent on the dimensions and geometry of the opening itself. For relatively large openings with flow paths, such as purpose provided vents and perhaps large cracks around ill-fitting windows, air flow tends to be turbulent and can be represented by the common orifice flow equation given by

$$Q = C_d A \left[\frac{2}{\rho} \Delta p\right]^{\frac{1}{2}} \quad (m^3/s) \qquad (3.1)$$

where
$Q$ = air flow rate ($m^3/s$)
$C_d$ = discharge coefficient
$\rho$ = air density ($kg/m^3$)
$\Delta p$ = pressure difference across opening (Pa)
$A$ = area of opening ($m^2$)

For very narrow cracks with relatively long flow paths, such as may be found in mortar and between tight fitting components, the nature of flow at ambient pressures is altogether very different and is dominated by the effects of viscosity. Flow through such openings is essentially laminar with the flow rate being directly proportional to the applied pressure difference. Taking pipe flow as an analogy, the flow rate can be approximated by

$$Q = \frac{\Delta p}{8\mu L} \pi r^4 \qquad (m^3/s) \qquad (3.2)$$

where $\mu$ = dynamic viscosity

$L$ = length of flow path (m)

$r$ = radius of opening (m)

In reality, some combination of these two regimes is common and the flow rate can normally be represented by the power law equation

$$Q = k(\Delta p)^n \qquad (m^3/s) \qquad (3.3)$$

where $k$ = flow coefficient ($m^3$/s at 1 Pa)

$n$ = flow exponent

$\Delta p$ = pressure difference across opening (Pa)

The coefficient, k, is related to the size of the opening and the exponent, n, characterises the flow regime. The flow exponent ranges in value from between 0.5 for fully turbulent flow to 1.0 for laminar flow.

It is often necessary to determine the flow performance of ducts and chimneys by measurement of their physical parameters. For such openings, the duct flow equation given by

$$Q = A \left[ \frac{2A}{E} \cdot \frac{1}{f \ell \rho} \cdot \Delta p \right]^{\frac{1}{2}} \qquad (m^3/s) \qquad (3.4)$$

where $A$ = cross sectional area of opening ($m^2$)

$E$ = cross sectional perimeter (m)

$f$ = friction coefficient

$\ell$ = length of duct (m)

$\rho$ = air density ($kg/m^3$)

For reasons of dimensional homogenity, a quadratic formulation of the flow equation in which the turbulent and laminar flow components are separated is sometimes preferred. The form of the quadratic equation is given by

$$\Delta p = \alpha Q + \beta Q^2 \qquad (3.5)$$

where $\alpha$ and $\beta$ are constants

Virtually all infiltration models utilise one or more of the above equations to represent air flow through openings.

### 3.1.2 Ventilation Efficiency

Imperfect mixing is likely to occur in instances where convective currents create circulatory or preferential air flow patterns leaving zones in which air is effectively trapped. This problem is further aggravated by the improper siting of supply and exhaust terminals. The degree and nature of mixing is frequently described in terms of ventilation efficiency in which three extremes of mixing characteristics are defined[1]. The first and most 'efficient' is known as 'plug flow' or 'piston flow' in which fresh air displaces contaminated air directly. The second is 'perfect mixing' in which incoming air continuously and uniformly mixes with the interior air mass. The final extreme is that of total short-circuiting. This condition is represented by the complete interception of supply air by the exhaust air register without any mixing with the interior air mass. Typical examples of the ventilation efficiency of various air distribution configurations are illustrated in Figure 3.1. The general assumption adopted in this design guide is that perfect mixing is achieved within each zone. Further information on the design and location of air inlet/outlet openings for optimum ventilation efficiency is covered in detail by Sandberg[1].

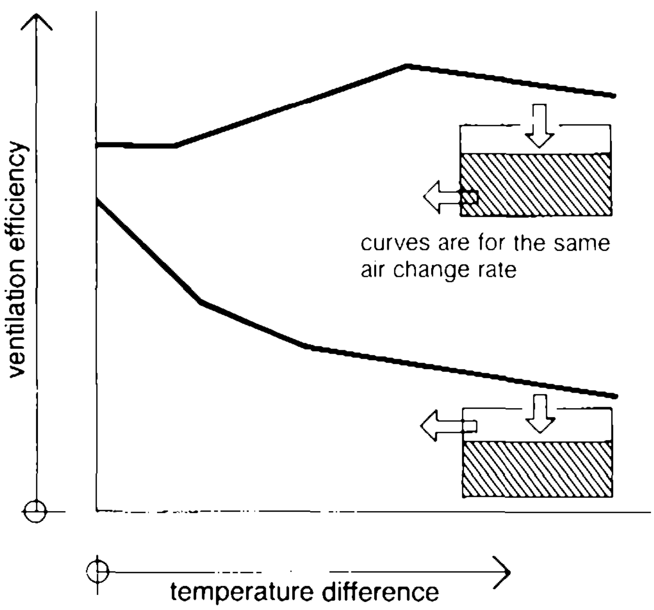


Figure 3.1 Ventilation efficiency in occupied zones (shaded area) for alternative ventilation configurations

### 3.1.3 Driving Forces

The forces driving air exchange are maintained by the natural actions of wind and temperature and by the pressures induced by the operation of mechanical ventilation systems. As with the flow approximations, considerable simplification of the true pressure distribution is necessary in any mathematical treatment of the driving force.

#### 3.1.3.1 Wind Induced Pressure Distribution

Wind within the lower regions of the earth's atmosphere is characterised by random fluctuations in velocity which, when averaged over a fixed period of time, possess a mean value of speed and direction. The strength of the wind is also a function of height above ground, this function being dependent on surface or terrain roughness, and on the thermal nature of the atmosphere (thermal stability).

On impinging the surface of an exposed rectangular building, wind deflection induces a positive pressure on the upwind face. The flow separates at the sharp edges of the building, giving rise to negative pressures along the sides. Negative pressures are also experienced within the wake region on the leeward face (Figure 3.2).

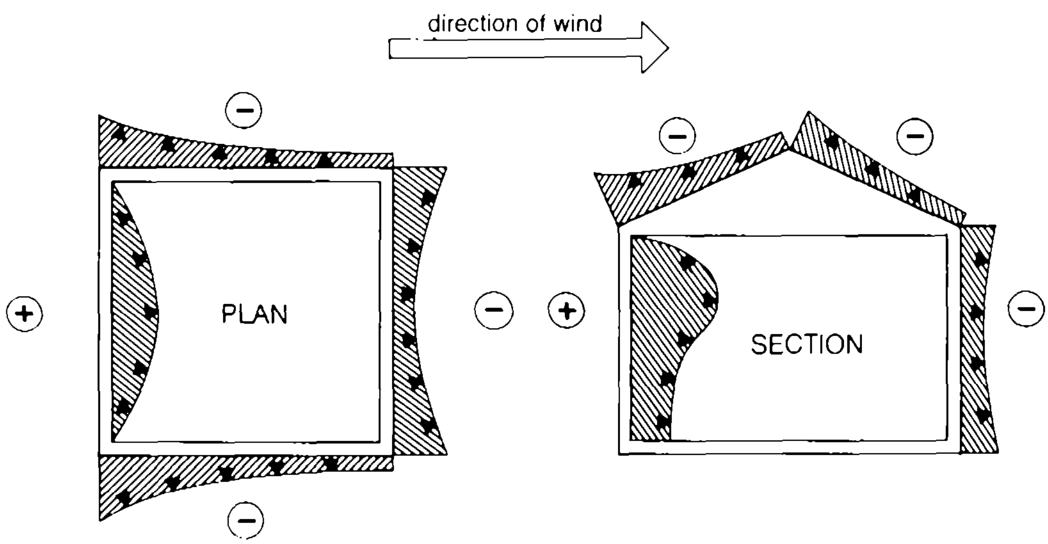


Figure 3.2 Wind pressure distribution on building

The pressure distribution on the roof varies according to pitch, with negative pressures being experienced on both faces for roof pitches of less than approximately 30°. Above this angle, positive pressures are experienced on the leading face (Figure 3.3).

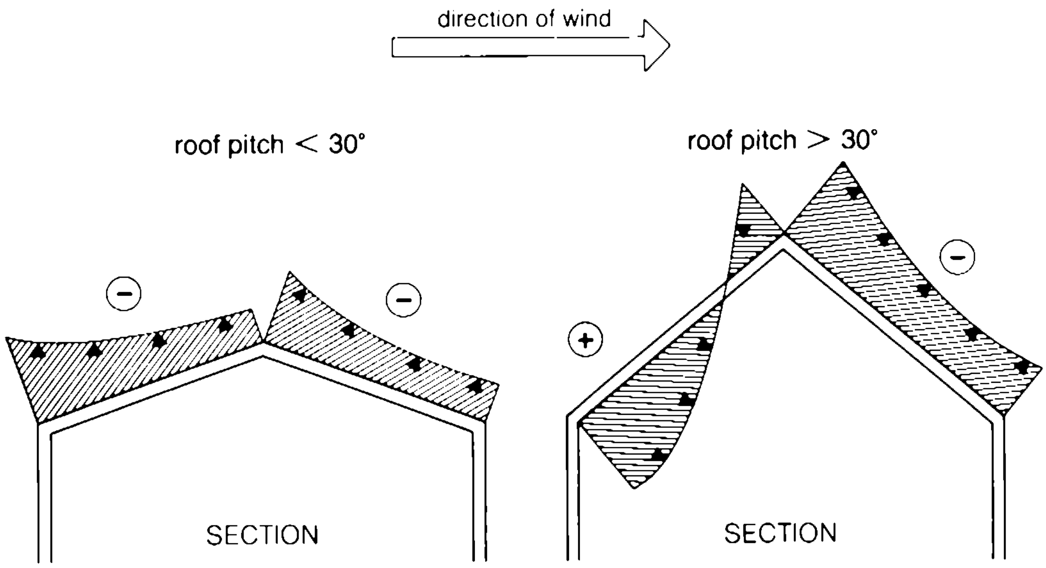


Figure 3.3 Wind pressure distribution according to roof pitch angle

Wind incident to the corner of the building will induce a net positive pressure on both upwind faces but, as flow veers towards a particular side, the remaining face will undergo a transition from positive to negative pressure (Figure 3.4). The angle at which this transition occurs is dependent on the side ratio of the building. For buildings with ventilated roof spaces, wind will directly affect the ceiling pressure distribution (Figure 3.5).

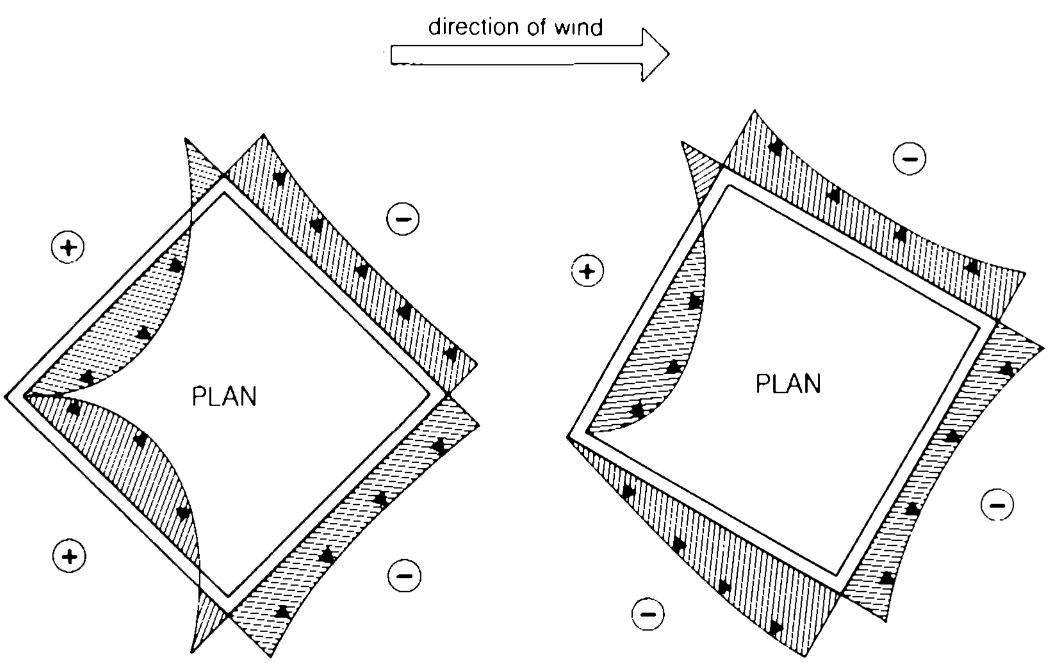


Figure 3.4 Pressure distribution due to wind incident on the corner of a building

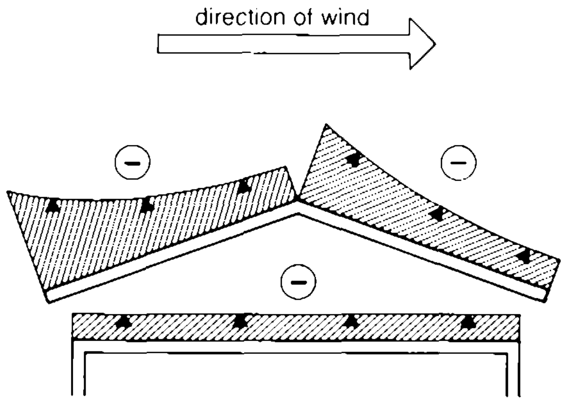


Figure 3.5 Wind pressure distribution in ventilated roof spaces

Other considerations include protrusions from roofs such as chimneys and flues. The pressure due to wind acting on the mouths of such components is a function of position, roof pitch and height of protrusion [2,3].

In general it is observed that relative to the static pressure of the free wind, the time averaged pressure acting at any point on the surface of a building may be represented by the equation

$$P_w = \frac{\rho}{2} C_p V^2 \qquad (3.6)$$

where $P_w$ = surface pressure due to wind (Pa)

$C_p$ = pressure coefficient

$V$ = mean wind velocity at datum level (usually building height) (m/s)

Since the strength of the wind close to the earth's surface is influenced by the roughness of the underlying terrain and the height above ground, a reference level for wind velocity must be specified for use in the wind pressure calculation. For the purposes of this publication, wind velocity is expressed at building height unless otherwise stated in the text.

As a rule, "on-site" data is rarely available and therefore measurements taken from the nearest climatalogical station must be applied. However, it is essential that such measurements are corrected to account for any difference between measurement height and building height and to account for intervening terrain roughness. By nature of the square term in equation 3.6, wind pressure is very sensitive to the wind velocity and, as a consequence, the arbitrary use of raw wind data will invariably give rise to misleading results. This is, perhaps, one of the most common causes of error in the calculation of air infiltration rates.

Suitable correction for the effects of these parameters may be achieved using a power law wind profile equation[4] of the form

$$\frac{V}{V_m} = \alpha z^{\gamma} \qquad (3.7)$$

where $\alpha$ and $\gamma$ are coefficients according to terrain roughness (Table 6.2.7, Section 6.2)

$z$ = datum height (m)

$V$ = mean wind speed at datum height (m/s)

$V_m$ = mean wind speed at weather station (m/s)

Such an approach is generally acceptable for winds measured between roof height and a recording height of 10m. It is inappropriate for the reduction of wind speeds measured in the upper atmosphere.

Details and data covering the correction of wind speed are presented in part 6.2 of the Data Reference Section.

The magnitude of the effects of local shielding and terrain on the wind pressure is presented as a worked example in Chapter 5.2.

The pressure coefficient, $C_p$, is an empirically derived parameter which is a function of the pattern of flow around the building. It is normally assumed to be independent of wind speed but varies according to wind direction and position on the building surface. It is also significantly affected by neighbouring obstructions with the result that similar buildings subjected to different surroundings may be expected to exhibit similar markedly different pressure coefficient patterns. Accurate evaluation of this parameter is one of the most difficult aspects of air infiltration modelling and, as yet, is not possible by theoretical means alone. Although pressure coefficients can be determined by direct measurements of buildings, most information comes from the results of wind loading tests made on scale models of isolated buildings in wind tunnels. Examples of such coefficients for simple building shapes are given in BS5925[4]. However, there are limitations regarding the applicability of these results in infiltration studies, since very often no consideration is given to the shielding effects of surrounding obstructions. Furthermore, the wind regime selected for each test tends to reflect adverse rather than normal conditions. Purpose designed tests for specific buildings and shielding conditions may be performed, but this is an expensive exercise and is therefore rarely possible.

For low buildings of up to typically 3 storeys, pressure coefficients may be expressed as an average value for each face of the building and for each $45^o$ sector, or even $30^o$ sector in wind direction. Typical design data based on published results are presented in section 6.2 of the data reference section. These have been compiled from the results of an extensive bibliographic search and from the results of an AIC workshop on wind pressure data for air infiltration calculations[5]. The compiled data is by no means exhaustive and should be regarded as approximate only.

For taller buildings, the spatial distribution of wind pressure takes on much greater significance, since the strength of the wind can vary considerably over the height range. This problem can be overcome by the use of local pressure coefficients to define the wind pressure at any specific location on the building face. Unfortunately, alternative definitions of this parameter exist, none of which are interchangeable.

The first possibility is to retain the concept of a reference wind speed height but to specify individual coefficients on each face of the building according to an array or network of points. This is the method chosen by Bowen[6], who has published a complete data set of local wind pressure coefficients for a 2:1 rectangular shaped wind tunnel building surrounded by obstructions of varying size. A summary of Bowen's data depicting the vertical distribution of pressure coefficient for each face is reproduced section 6.2. The data may be used as a direct substitute for the average pressure coefficient data recommended for low rise buildings.

An alternative approach is suggested by Akin[7] who has attempted to express the vertical pressure distribution by a single "local" pressure coefficient. It is defined by the equation

$$(P_w)_z = \frac{\rho}{2} C_{pi} V_z^2 \qquad (3.8)$$

where $(P_w)_z$ = surface pressure at height, z, due to wind (Pa)

In other words the pressure is based on the wind speed in the approach flow at the height of the location of interest and not building height. Clearly the resultant pressure coeffieint is very much different to that used by Bowen or as used in a number of wind pressure codes. This approach is not directly compatible with the algorithms presented in this guide.

3.1.3.2 Turbulent Fluctuations

The turbulent nature of the atmospheric wind results in corresponding fluctuations to the wind induced pressure distribution. These fluctuations span a wide frequency spectrum with the most significant value resulting from the combined effects of local terrain roughness and eddy shedding from upwind directions. These transient departures from the mean pressure distribution are not represented by the use of steady state pressure coefficients and are therefore normally neglected in mathematical modelling studies. However, there are instances in which it can be shown by experiment that pressure fluctuations contribute an additional component to the rate of air infiltration. This is most likely to occur when the mean pressure difference across an opening is small in comparison to the size of the fluctuating component. Oscillating movements of air are then free to pass through the building envelope and to mix with the internal air mass. One such example is depicted in Figure 3.6(a). Small openings are located on the opposite faces of an otherwise sealed enclosure. If flow is directed parallel to these openings, the mean wind pressure acting on both faces will be similar and therefore a steady state formulation of the flow equation will indicate zero infiltration. In practice, however, air exchange may be shown to occur[8]. A second example is considered in Figure 3.6(b). This time the enclosure has a single opening which is directly aligned with the oncoming wind. Since there is no exfiltration path, the internal pressure rises match that acting on the outside face. Again, air infiltration is observed in practice although a steady-state analysis will reveal a negligible infiltration rate.

This second example has particular relevance when considering wind-induced flow through window and door openings, when the area of opening in one face is considerably greater than those of the remaining sides of the building.

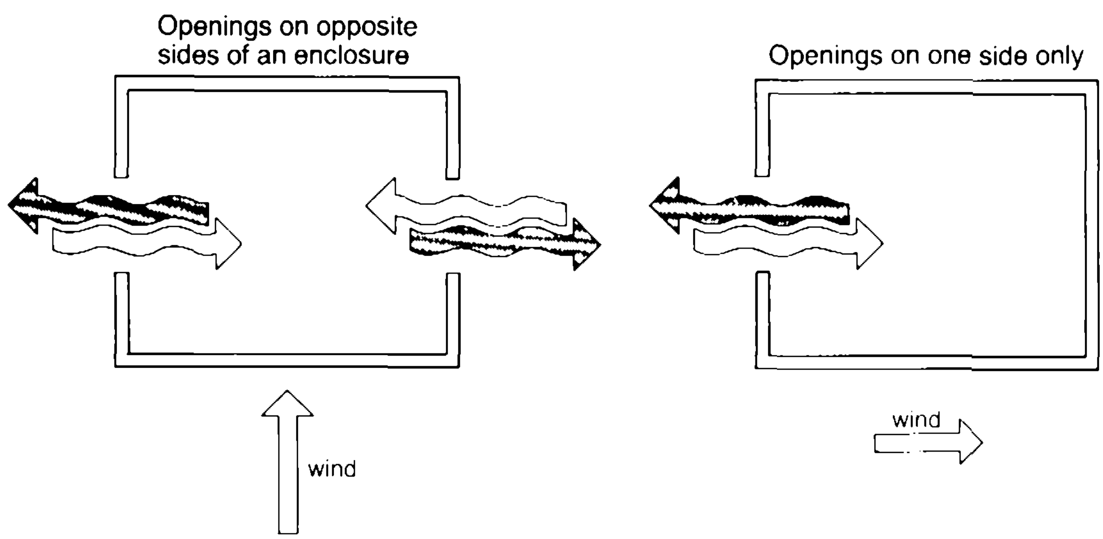


Figure 3.6 Air infiltration due to turbulent fluctuations

Equations which have been introduced to make allowances for turbulent fluctuations are of an empirical nature and tend to be based on the results of laboratory observations. Etheridge[9] for example, assumes that the turbulent pressure distribution with respect to time, $p_i(t)$ has a Gaussian distribution and that the resultant flow is given by

$$\overline{Q}_{T_i} = F \; \frac{0.4\sqrt{2}}{\pi} \; \frac{\Delta p_{i_{rms}}}{\overline{\Delta p_i}} \; \overline{Q}_i \qquad (3.9a)$$

where F is a linear function which accounts for large mean pressures and is arbitrarily set such that

$\overline{Q}_{T_i}$ = $\rightarrow 0$ as $\overline{\Delta p_i} \rightarrow 3$

$\overline{Q}_i$ = steady state flow rate through opening

$\Delta p_{i_{rms}}$ = root mean square pressure difference across opening

The response to internal pressure resulting from external pressure fluctuations is unknown but is assumed to have the relationship

$$\Delta p_{i_{rms}} = 0.5 \; p_{i_{rms}}$$

where $p_{i_{rms}}$ = root mean square value of surface pressure fluctuations. It is assumed to be uniform over the surface of the building and is calculated on the basis of a pressure coefficient, $C_p$, of 0.3.

De Gids[10] also considers a correction formula which is based on the magnitude of the steady state pressure imbalances.

$$Q_{vol} = \frac{A}{2} \left(0.0001 V^2 + 0.0035 h \Delta T + 0.01\right)^{1/2} \qquad (3.9b)$$

where A = area of opening ($m^2$)

h = height of opening (m)

V = wind speed (m/s)

$\Delta T$ = internal/external temperature difference (K)

In terms of indoor air quality and energy implications, the significance of turbulent fluctuations in real buildings is uncertain. Equally, techniques to calculate the effects of this component have yet to be verified. However, having calculated the mean infiltration rate through openings, a turbulent component of infiltration can be easily determined using equations of the form 3.9a and 3.9b.

3.1.3.3 Stack Effect

The stack effect arises as a result of differences in temperature and hence air density between the interior and exterior of a building. This produces an imbalance in the pressure gradients of the internal and external air masses, thus creating a vertical pressure difference. When the internal air temperature is higher than that of the outside air mass, air enters through openings in the lower part of the building and escapes through openings at a higher level. This flow direction is reversed when the internal air temperature is lower than that of the air outside. The level at which the transition between inflow and outflow occurs is defined as the neutral pressure plane. In practice, the level of the neutral plane is rarely known although it can be predicted for straightforward leakage distributions. More generally, the stack pressure is expressed relative to the level of the lowest opening or to some other convenient datum (for example ground level).

In air infiltration studies, the consequences and significance of the stack effect must be considered for a number of alternative configurations. These include

* uniform internal temperature distribution
* multi-zone buildings with impermeably separated vertical zones
* multi-zone buildings in which interconnected vertically placed zones are at different temperatures
* multi-zone buildings in which horizontally placed zones are at different temperatures
* large single zone structures subjected to thermal stratification
* fireplaces, chimneys and flues

Each of these configurations may be readily analysed and combined by consideration of the vertical pressure gradient of the respective air masses.

Stack Effect:
Uniform Internal Temperature Distribution

For a uniform temperature, the pressure of an air mass at any height z above a convenient datum level, $z_o$, (for example ground or floor level) is given by

$$p_z = p_o - \rho g z \quad \text{(Pa)} \qquad (3.10)$$

where $p_o$ = pressure at datum level $z_o$

$g$ = acceleration due to gravity ($m/s^2$)

The corresponding pressure gradient is therefore

$$\frac{dp}{dz} = -\rho g$$

which becomes, by consideration of the gas laws,

$$\frac{dp}{dz} = -\rho_o g \frac{273}{T} \qquad (3.11)$$

where $\rho_o$ = air density at 273K ($kg/m^3$)

$T$ = absolute temperature of air mass (K)

Thus the pressure gradient is inversely proportional to the absolute temperature of the air mass.

Pressure gradients and the absolute pressure distribution for a building in which two openings, $h_1$ and $h_2$, are vertically separated a distance h apart are illustrated in Figure 3.7. The level of alignment of the internal and external pressures (neutral pressure plane) is a function of the overall distribution and flow characteristics of openings, and is fixed such that a mass flow balance is maintained. Knowledge of this level is not a pre-requisite of air infiltration modelling. The stack induced pressure at $h_2$, with respect to the pressure at $h_1$, is represented in Figure 3.7 by the net horizontal displacement of the pressure curves at these locations (A + B) and is given by

$$p_s = -\rho_o g \; 273 \; (h_2-h_1) \left[\frac{1}{T_{ext}} - \frac{1}{T_{int}}\right] \quad \text{(Pa)} \qquad (3.12)$$

where $T_{ext}$ = absolute external temperature (K)

$T_{int}$ = absolute internal temperature (K)

The calculation of stack pressure for typical temperature differences and displacement of openings is covered in section 5.2. Stack pressures are often of comparable significance to wind pressures. Typical comparisons are presented in Section 5.2.

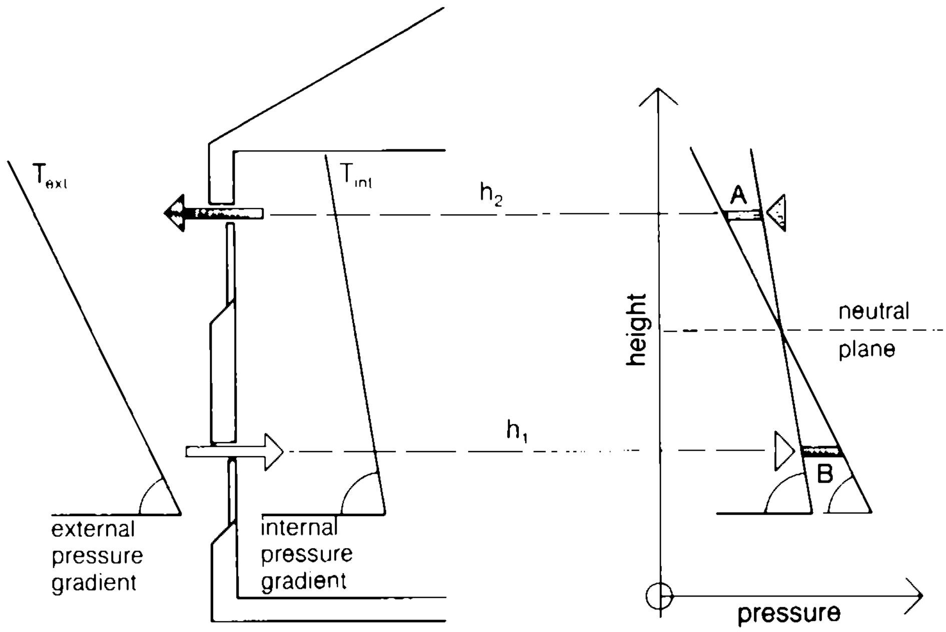


Figure 3.7 Stack induced pressure between two vertically placed openings

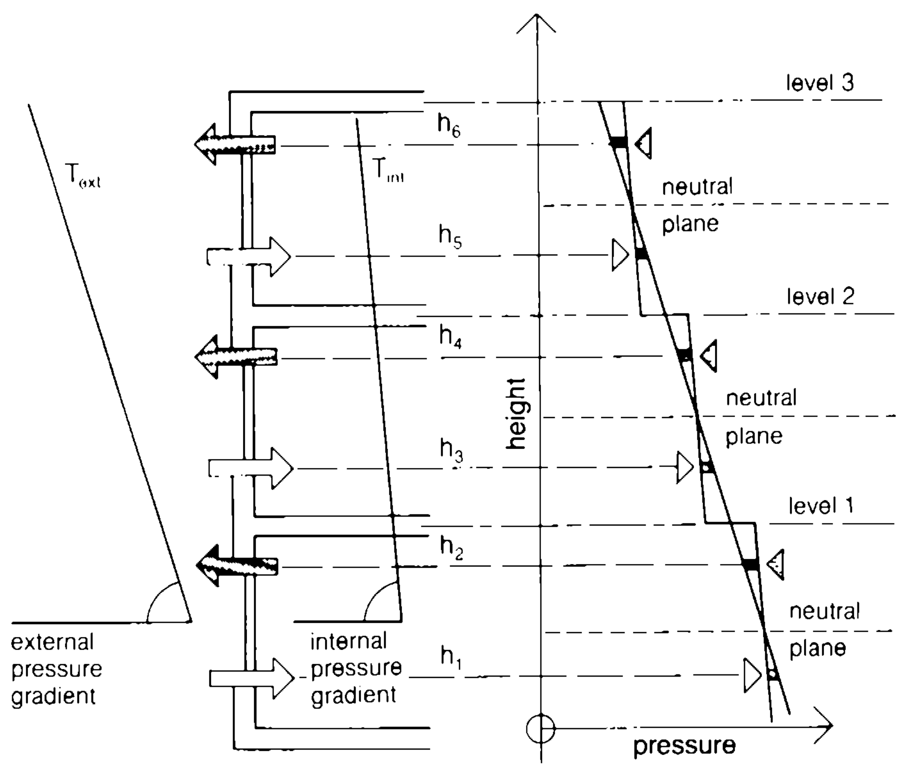


Figure 3.8 Stack pressure distribution in multi-storey buildings with isolated floors

Stack Effect:
Multizone Buildings with Impermeably Separated Vertical Zones

The stack pressure distribution of a building in which each floor is isolated by an impermeable barrier is illustrated in Figure 3.8. Each floor displays its own neutral pressure plane and it is possible to calculate the stack pressure distribution without reference to adjacent zones. However, special treatment of this case is not normally necessary and it is recommended that the stack pressure at any opening is again expressed relative to the lowest opening, that is, relative to $h_1$ or to ground level.

Stack Effect:
Multizone Buildings in which Vertically Interconnected Zones are at Different Temperatures

In practice, a uniform temperature distribution may not always be possible or even desired. By design or otherwise, it may be that the internal temperature of each zone will differ. In dwellings, for example, upstairs bedrooms are frequently maintained at a lower temperature to the living area, while a roof space might not be heated at all. The resultant stack pressure may be analysed in exactly the same way as the previous example, except that the pressure gradient of each cell varies according to the zonal air temperature (Figure 3.9). The stack pressure at any level is again given by the displacement in pressure gradients.

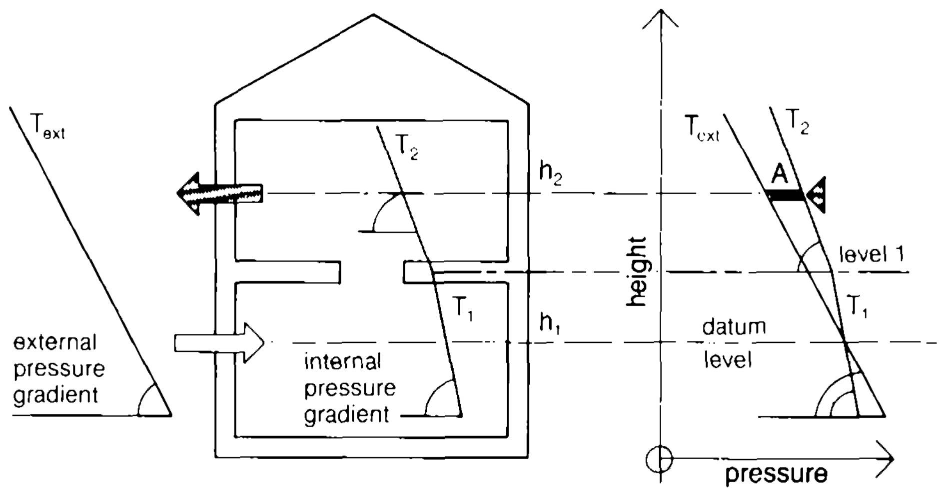


Figure 3.9 Stack pressure for vertically placed zones at different temperatures

For example, the stack pressure at $h_2$ with respect to $h_1$ (horizontal displacement 'A' in Figure 3.9) is given by

$$p_s = -\rho_o g\ 273 \left\{ (L_1 - h_1) \left[\frac{1}{T_1} - \frac{1}{T_{ext}}\right] + (h_2 - L_1) \left[\frac{1}{T_2} - \frac{1}{T_{ext}}\right] \right\} \quad \text{(Pa)} \qquad (3.13)$$

where $L_1$ = first floor level (see figure 3.9) (m)

$T_1$ = internal temperature of ground floor zone (K)

$T_2$ = internal temperature of first floor zone (K)

Stack Effect:
Multizone Buildings in which Horizontally Placed Zones are at Different Temperatures

This situation may occur in an office environment or multi-storey building in which the stairwell or public access areas are maintained at a lower temperature than the occupied parts of the building. Again, the temperature gradients in each of the zones are analysed as previously described with the stack pressure being expressed relative to the lowest opening. The corresponding stack pressures at other heights are then determined by the relative displacements (Figure 3.10).

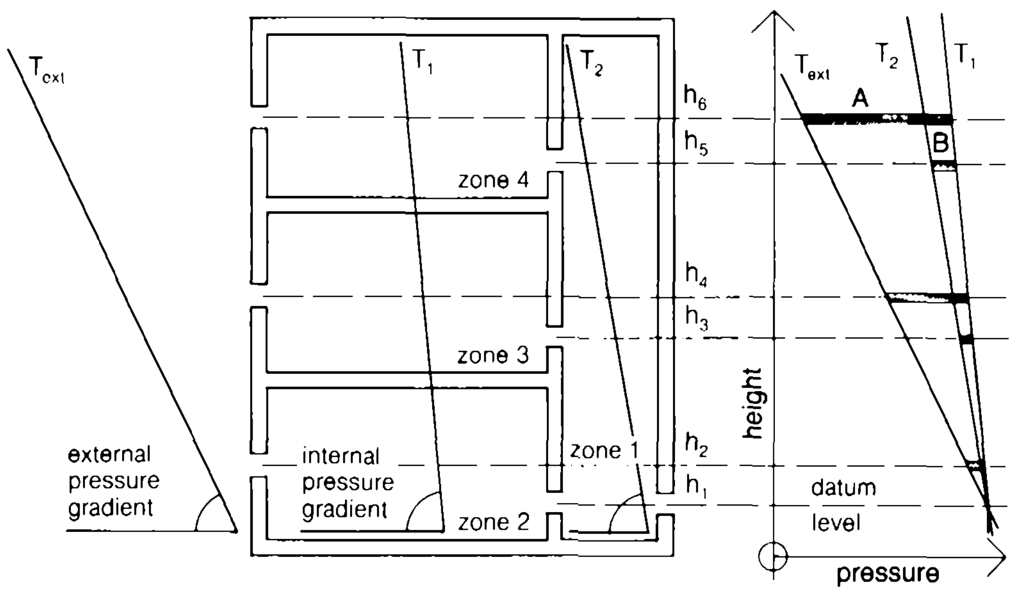


Figure 3.10 Stack pressure for horizontally spaced zones at different temperatures

Thus the stack pressure at $h_5$, between zone 1 and 4 (displacement 'B' in Figure 3.10) is given by

$$p_s = -\rho_o g \, 273 \, (h_5 - h_1) \left[\frac{1}{T_1} - \frac{1}{T_2}\right] \quad \text{(Pa)} \qquad (3.14)$$

where $T_1$ = temperature in each of the vertically stacked zones (K)

$T_2$ = temperature of zone 1 (see figure 3.10) (K)

Stack Effect:
Large Single-zone Structures Subjected to Thermal Stratification

This occurrence is frequently encountered in large factory and warehouse buildings where warm air rises to the roof space, resulting in a considerable amount of thermal stratification. Since the density of air is a function of the air temperature, a non-linear internal pressure gradient is created. For this situation, the pressure equation (equation 3.9) must be written to account for the dependency of density on height as follows

$$p_z = g \int_o^h \rho(z) \, dz \qquad (3.15)$$

where $\rho(z)$ = air density at height z ($kg/m^3$)

h = height of enclosure (m)

Substituting for vertical temperature distribution, $T_{(z)}$ yields

$$p_z = p_o - \rho_o g \, 273 \int_{z_o}^{z=h} \frac{1}{T_z} dz \quad \text{(Pa)} \qquad (3.16)$$

Equation 3.16 can be analysed for almost any function of T but, for this example, the temperature is assumed to be linearly dependent on height, ie

$$T_z = \omega z + T_{z_o} \quad \text{(K)} \qquad (3.17)$$

where $\omega$ = temperature gradient (K/m)

$T_{z_o}$ = temperature at height, $z_o$ (K)

$$\therefore \quad p_z = p_o - g\rho_o 273 \int_{z_o}^{h} \frac{1}{\omega z + T_{z_o}} \cdot dz \qquad (Pa) \qquad (3.18)$$

Hence, for $\omega = 0$

$$p_z = p_o - g\rho_o \frac{273}{T_{z_o}} \left[ z \right]_{z=o}^{z=h} \qquad (Pa) \qquad (3.19)$$

and, for $\omega \neq 0$

$$p_z = p_o - g\, \rho 273 \left[ \frac{1}{\omega} \, Ln\, (\omega z + T_{z_o}) \right]_{z=o}^{z=h} \qquad (Pa) \qquad (3.20)$$

Taking the gradient

$$\frac{dp}{dz} = \frac{-g\rho_o 273}{(\omega z + T_{z_o})} \qquad (3.21)$$

Thus, for $\omega = 0$, equation 3.21 is compatible with equation 3.14.

Having established the pressure gradient equation, the stack pressures are calculated as previously described (Figure 3.11).

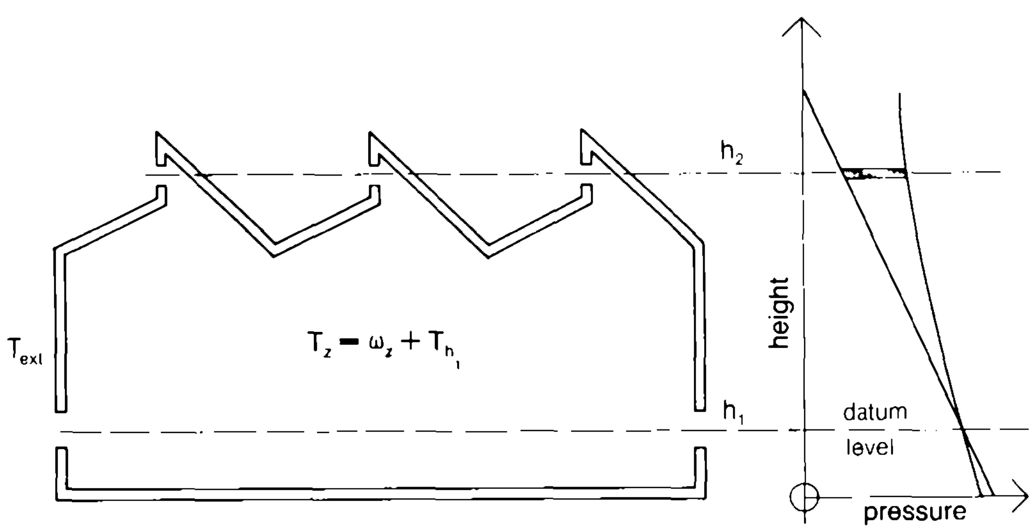


Figure 3.11 Stack pressure due to internal temperature gradient

Flues and Chimneys

Flues and chimneys connected to heating appliances present a major air flow route. In addition, during furnace operation, they have an operating temperature well in excess of ambient room temperatures. The resultant stack influence is considerably enhanced but may nevertheless be readily calculated using the standard principles governing stack pressures.

### 3.1.3.4 Combined Wind and Stack Effect

So far the effects of wind and temperature have been considered in isolation whereas in reality they combine to form a total pressure distribution. Air infiltration calculated from wind and stack effect acting alone should not be summed directly to obtain a combined air infiltration rate. The respective component pressures, however, can be summed to obtain the total pressure at each opening. Thus the pressure at any opening, i, is given by

$$p_i = p_{w_i} + p_{s_i} \qquad \text{(Pa)} \qquad (3.22)$$

Provided the magnitude of the pressures are known, then the combined influence of wind and temperature can be readily incorporated into a mathematical model.

In order to simplify calculation techniques, the concept of a separate stack component and wind component of air infiltration is sometimes retained[11]. Experimental observation has indicated that such an arrangement is possible if the corresponding infiltration values are added in quadrature to obtained the total infiltration rate, ie

$$Q_T = (Q_w^2 + Q_s^2)^{\frac{1}{2}} \qquad (m^3s^{-1}) \qquad (3.23)$$

where $Q_T$ = total infiltration

$Q_w$ = infiltration due to wind

$Q_s$ = infiltration due to stack

The latter approach has special relevance in equivalent leakage area type models (Section 5.1).

### 3.1.3.5 Pressure Effects due to Mechanical Ventilation

Mechanical ventilation may be analysed in terms of the induced flow rate and pressure imbalance created across the fan and associated ducting. The resultant pressure difference becomes another component to the total pressure equation.

The additional pressure imbalance created by an extract only ventilation system is very straightforward to calculate by direct application of the exponential flow equation (equation 3.3). If the total leakage coefficient, as determined by a pressurisation test, for the zone within which the extract fan or duct is located is given by $K_t$ and the flow rate through the fan is given by $Q_{mv}$, then the pressure imbalance is

$$(\Delta p_{mv})^n = \frac{Q_{mv}}{k_t} \qquad \text{(Pa)} \qquad (3.24)$$

where $n$ = flow exponent

In practice the pressure effect due to mechanical ventilation is calculated automatically within an air infiltration model. In its simplest form, mechanical ventilation is incorporated into a model by specifying the design flow rate for the zone or zones in which mechanical ventilation is present. The appropriate internal/external pressure difference to ensure mass balance then forms part of the mass balance calculation. Equation 3.24 serves as a useful design check to ensure that excessive under-pressures are avoided (see Section 4.3.1) or to ensure that the system can function correctly at the induced pressure difference predicted. This latter consideration is most important as the validity of a 'fixed flow' assumption is dependent on the mechanical ventilation system being able to meet the required flow rate at the calculated pressure difference.

An alternative method is to treat ventilation as an additional flow path in which the pressure versus flow rate relationship is specified, that is,

$$Q_{mv} = f(\Delta p) \qquad (m^3/s) \qquad (3.25)$$

Assuming that the pressure difference created across the mechanical ventilation system itself is given by $\Delta p_{mv}$ and that the pressure difference created between the inside and outside of the building is given by $\Delta p_b$, then provided

$$\Delta p_{mv} >> \Delta p_b$$

the fixed flow assumption is valid. The alternative is to express $Q_{mv}$ by a quadratic relationship given by

$$Q_{mv} = a_1 + b_1(\Delta p_{mv}+\Delta p_b) + c_1(\Delta p_{mv}+\Delta p_b)^2 \qquad (m^3/s) \qquad (3.26)$$

## 3.2 THEORETICAL CALCULATION TECHNIQUES

### 3.2.1 Single-Zone Network Models

This approach is used to calculate infiltration into a single enclosed space. Model parameters include

* flow path distribution (Section 3.3.1)
* flow path characteristics (k and n values - see Section 3.3.2)
* building height
* internal/external temperature difference
* local wind speed (or reduced from remote site) (Section 3.1.3.1)
* local shielding conditions
* terrain roughness parameters
* characteristics of mechanical ventilation system

Any number of flow paths, terminating within the internal zone, can be selected to represent leakage openings in each face of the building (Figure 3.12 and Section 3.3.1).

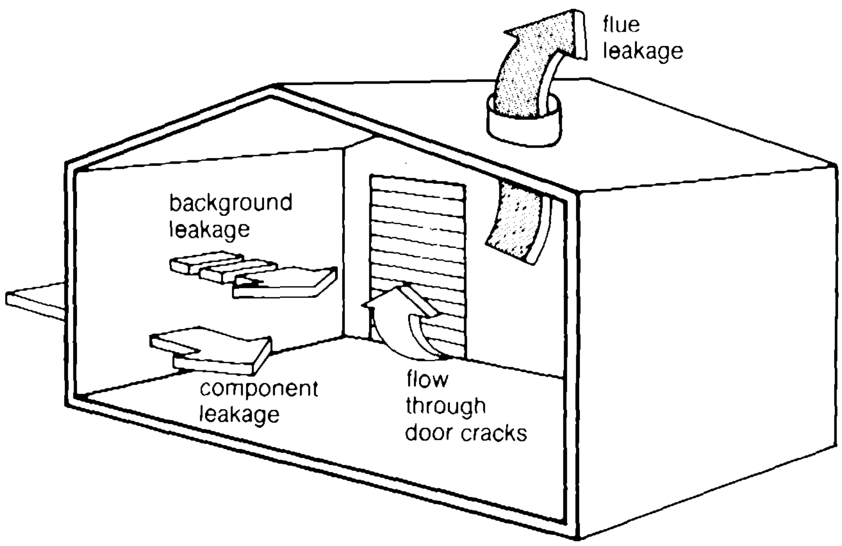


Figure 3.12 Single zone network

For j such flow paths, a mass flow balance is given by

$$\sum_{i=1}^{j} \rho_i Q_i = 0 \qquad \text{(kg/s)} \qquad (3.27)$$

where $\rho_i$ = density of air flowing through i'th flow path (kg/m$^3$)

$Q_i$ = volumetric flow rate (m$^3$/s)

By substitution of the above in the power law form of the flow equation (equation 3.3), the condition of mass balance becomes

$$\sum_{i=1}^{j} \underbrace{\rho_i}_{\text{Term 1}} \underbrace{k_i \left| p_i - p_{int} \right|^{n_i}}_{\text{Term 2}} \underbrace{\left( \frac{p_i - p_{int}}{\left| p_i - p_{int} \right|} \right)}_{\text{Term 3}} = 0 \qquad (3.28)$$

where $k_i$ = flow coefficient of the i'th flow path

$n_i$ = flow exponent of the i'th flow path

$p_i$ = external pressure acting on the i'th flow path

$p_{int}$ = internal pressure

$\rho_i$ = density of air mass in the i'th flow path

The infiltration air density, $\rho_i$, is given by that of the outside air while for the exfiltrating air it is given by that of the internal air mass. If the density differences between the internal and external air masses are negligible in comparison to the magnitude of the overall density of air, ie when the internal/external temperature difference is less than approximately 20$^o$C, then Term 1 of equation 3.25 may be ignored. The problem then becomes one of balancing the volume flow rate rather than the mass flow rate. Term 2 expresses the absolute value of the internal/external pressure difference across each opening and is applied to avoid exponentiating a negative number when $p_i < p_{int}$. Term 3 restores the sign of the flow direction which was lost in the previous term.

Hence

For $p_i > p_{int}$, Term 3 = 1

For $p_i < p_{int}$, Term 3 = -1

The sign convention for the direction of flow is therefore +ve for infiltration or air movement into a zone and -ve for exfiltration or air flow out of a zone.

The values of $k_i$, $n_i$ and $p_i$ must be specified for each flow path (see Section 3.3), leaving the internal pressure, $p_{int}$, as the only unknown.

The infiltration rate is given by

$$Q_{inf} = \sum_{i=1}^{j} Q_i \quad (\text{for } Q_i > 0) \qquad (m^3/sec) \qquad (3.29)$$

and the hourly air change rate is given by

$$ACR = \frac{3600\ Q_{inf}}{Vol} \qquad (h^{-1}) \qquad (3.30)$$

where Vol = internal volume of zone ($m^3$)

Mechanical Ventilation

Extract or supply ventilation is most easily incorporated by expanding the mass balance equation (3.24) to give

$$\sum_{i=1}^{j} \rho_i Q_i + \rho_i Q_{mv} = 0 \qquad (kg/s) \qquad (3.31)$$

For extract ventilation $Q_{mv}$ is -ve and the air density, $\rho_i$, corresponds to that of the internal air mass. For supply ventilation $Q_{mv}$ is +ve and the air density corresponds to that of the external air mass. This approach is valid provided that the design flow rate through the system can be achieved at the induced pressure difference across the system. If it cannot, then $Q_{mv}$ must be specified as a function of pressure, or alternatively the internal pressure must be relieved by the inclusion of air vents.

Balanced supply/extract ventilation has no influence on the internal pressure of a single zone structure and therefore the air flow rate is summed directly to the calculated infiltration rate, ie

$$Q_{total} = Q_{inf} + Q_{balanced} \qquad (m^3/sec) \qquad (3.32)$$

and the air change rate is given by

$$ACR = \frac{Q_{total} \times 3600}{Vol} \qquad (h^{-1}) \qquad (3.33)$$

The single cell network approach offers many advantages. These include

* comparative ease of calculation

* the incorporation of any number of flow paths

* the inclusion of any combination of wind, stack and mechanically induced pressures

* the ability to assess the effect of flow path distribution change rates

* the ability to identify the flow direction and the magnitude of the flow rate through each of the defined openings

* the calculation of internal pressure

* the ability to determine the neutral pressure plane using the external and internal pressure data

The principle disadvantages of the single cell network approach are its more demanding data needs and its unsuitability for multi-zone buildings. Examples using this approach are presented in Section 5.2.

### 3.2.2 Multi-Zone Network Models

If internal partitioning presents an impedence to the movement of air, then, for most design purposes, a multi-cell or multi-zone technique must be applied. Possible exceptions may only be permissible for the following circumstances:

* when an absolute 'maximum only' infiltration estimate is required

* when internal doors are very leaky or are generally left open

* when air circulation systems link each room, eg small air handling systems for dwellings

There are therefore many instances in which single zone approaches will be of little value and, as a result, consideration must be given to an internal flow structure. A typical multi-zone network is illustrated in Figure 3.13.

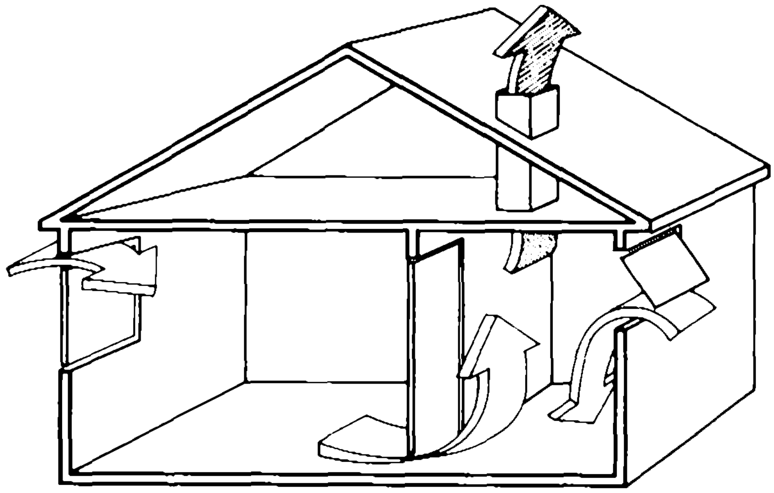

Figure 3.13 Multi zone network

Similar model parameters to the previous network approach apply, including

* flow path distribution (external and internal - section 3.3.1)
* flow path characteristics
* building height
* internal/external temperature differences
* wind speed (on site or remote - section 3.1.3)
* local shielding conditions
* terrain roughness parameters
* details of mechanical ventilation system

Again, any number of flow paths, terminating within each internal zone, can be selected to represent leakage openings in the building envelope. Additionally paths are selected to represent leakage openings across internal zones (Section 3.3.1). For the m'th such zone with a total of $j_m$ flow paths, the mass flow balance is given by

$$\sum_{i_m=1}^{j_m} \rho_{im} Q_{im} = 0 \quad \text{(kg/s)} \qquad (3.34)$$

where $Q_{im}$ = volumetric flow rate through the i'th flow path of the m'th node.

$\rho_{im}$ = density of air flow through the i'th flow path of the m'th node (kg/m$^3$)

Analagous to the single cell version (equation 3.25), substitution of the above in the power law form of the flow (equation 3.3) gives

$$\sum_{i_m=1}^{j_m} \rho_{im}\, k_{im} \left| p_{im} - p_m \right|^{n_{im}} \left( \frac{p_{im} - p_m}{\left| p_{im} - p_m \right|} \right) = 0 \qquad (3.35)$$

where $k_{im}$ = flow coefficient of the i'th flow path of the m'th zone

$n_{im}$ = flow exponent of the i'th flow path of the m'th zone

$p_{im}$ = pressure of zone adjacent to the m'th node across which the i'th flow path connects

$p_m$ = internal pressure of m'th node

The mass balance equation must apply to each zone. Therefore, assuming a total of q zones, total mass balance is given by

$$\sum_{m=1}^{q} \sum_{i_m=1}^{j_m} \rho_{im}\, K_{im} \left| p_{im} - p_m \right|^{n_{im}} \left( \frac{p_{im} - p_m}{\left| p_{im} - p_m \right|} \right) = 0 \qquad (3.36)$$

Unlike the 'single zone' approach, where there was only one internal pressure to determine, there are now many values. This adds considerably to the complexity of the numerical solution method. Suitable algorithms are outlined in Section 5.1.

The total flow into each zone will generally consist of components of air infiltration and of interzone air movement, thus the summation of the total flow into each zone will not necessarily yield the total infiltration or fresh air exchange rate. An extreme example would be a completely recirculatory system within an airtight structure, in which case there would be no fresh air exchange at all. Therefore, for the purposes of calculating the infiltration rate (both within individual zones and for the building as a whole), it is necessary to identify and to calculate the inflow through each of the external flow paths. This can be easily accomplished by identifying boundary flow paths and restricting the summation of infiltrating flow only to these paths.

Mechanical extract or supply only ventilation is analysed in an identical way to the single zone flow network approach, with the ventilation rates being applied to the appropriate zones.

Balanced supply/extract systems can also be analysed using the multi-zone approach since the supply and exhaust terminals are normally located in different zones. Thus the inter-zonal air distribution pattern generated by the installation of a balanced ventilation system may also be readily determined.

The multi-zone approach therefore offers an almost unlimited potential for analysing air infiltration and ventilation air flow distribution in compartmentalised buildings. In particular, because it may be used to predict internal air movement, it are an invaluable aid to indoor air quality studies. It may also be adapted to predict smoke movement within buildings. The main disadvantages are that it requires substantial data to describe the internal (and external) flow network and that it often demands a significant amount of computational effort. With care, however, these disadvantages may be minimised by tailoring the size of the flow network to suit the problem to be solved.

### 3.2.3 Simplified Theoretical Techniques

A number of "simplified" methods have been introduced in an effort to minimise the computational effort of theoretical techniques yet enable some of the accuracy of these methods to be retained. As yet they are only applicable to single zone structures and only provide estimates of infiltration. They give no indication of the pattern of air distribution. Two such methods have been analysed by the Air Infiltration Centre and have been found to give satisfactory results for a range of dwellings and climatic conditions[12]. These methods have been developed by the Building Research Establishment in the United Kingdom (BRE model)[13] and the Lawrence Berkeley Laboratory in the United States (LBL Model)[11].

The purpose of the BRE method is to provide a technique for relating air infiltration rate for any given set of conditions to the leakage characteristics of the building as determined by a pressurisation test. Air movement under ambient conditions is described by the power law equation

$$Q_v = Q_T \left[\frac{\rho_o V^2}{\Delta p_T}\right]^n F_v(A_r \emptyset) \qquad (m^3/s) \qquad (3.37)$$

where
- $Q_v$ = ambient flow rate ($m^3/s$)
- $Q_T$ = flow rate at an arbitrarily chosen reference pressure ($m^3/s$)
- $\rho_o$ = air density ($kg/m^3$)
- $V$ = wind speed at roof ridge height (m/s)
- $\Delta p_T$ = internal/external pressure difference (Pa)
- $F_v$ = infiltration rate function (see text)
- $A_r$ = Archimedes number
- $\emptyset$ = surface pressure function

For wind action alone, this equation reduces to

$$Q_w = Q_T \left[\frac{\rho_o V^2}{\Delta p_T}\right]^n F_w (\emptyset) \qquad (m^3/s) \qquad (3.38)$$

where $F_w$ = wind infiltration function

While for stack effect only, the flow equation becomes

$$Q_s = Q_T \left[\frac{\Delta T \rho g h}{T_I \Delta p_T}\right]^n F_B \qquad (m^3/s) \qquad (3.39)$$

where $F_B$ = stack infiltration function

$\Delta T$ = internal/external temperature difference (K)

$T_I$ = internal temperature difference (K)

$g$ = acceleration due to gravity (m/s)

$h$ = height of building (m)

The infiltration function $F_B$ is determined by the building shape and the distribution of leakage; $F_w$ in addition depends upon the surface pressure coefficients, while $F_V$ includes the effects of the major weather dependent parameters V and T.

The LBL model was developed to predict the impact on air infiltration rates of retrofit and other changes in the building envelope using the minimum number of model parameters. The model was specifically designed for simplicity and therefore precise detail was sacrificed for ease of application.

The building is approximated by a single rectangular structure of "single zone" construction, through which air flow is described by the equation

$$Q = A \left[\frac{2}{\rho} \Delta p\right]^{\frac{1}{2}} \qquad (m^3/s) \qquad (3.40)$$

where $A$ = effective leakage area ($m^2$)

$\rho$ = air density ($kg/m^3$)

$\Delta p$ = internal/external pressure difference (Pa)

The effective leakage area, A, is determined by means of a building pressurisation test or may be taken from the data presented in the ASHRAE Fundamentals (Chapter 22)[14]. The rates of air infiltration due to wind and stack driven pressure differences are calculated independently and are combined by summing the results in quadrature. The influence of mechanical ventilation systems is similarly included in the quadrature equation to yield a total ventilation rate of

$$Q_{total} = (Q^2_{stack} + Q^2_{wind} + Q^2_{vent})^{\frac{1}{2}} \quad (m\ /s) \qquad (3.41)$$

where $Q_{stack} = A\ f_s \Delta T^{\frac{1}{2}}$ = stack infiltration ($m^3/s$)

$Q_{wind} = f_w V_c$ = wind infiltration ($m^3/s$)

$Q_{vent}$ = flow rate of mechanical ventilation system ($m^3/s$)

$\Delta T$ = internal/external temperature difference (K)

$V_c$ = wind speed at ceiling height (m/s)

and $f_s$ and $f_w$ are stack and wind parameters respectively (see reference 9)

The LBL technique is covered in further detail in Section 5.1.1.

## 3.3 DATA REQUIREMENTS

As with any form of numerical modelling technique, the calculation of air infiltration rates demands the accurate interpretation of reliable design data. Ultimately, it is the availability and quality of appropriate data that dictates the choice of model and the overall accuracy of the approach. Basic design data must include a building and flow path description and also sufficient climatic and terrain data to calculate the surface pressure distribution. Requirements to support subsidiary calculations include ventilation performance data and indoor air quality information. Each of these needs is covered in this section. A standard format for recording the data is also included. Further information and guidelines can be found in the AIC's standard reporting format for the measurement of air infiltration in buildings[15].

Construction techniques and materials, internal layout and the overall design and location of buildings form the most basic input needs of air infiltration models. A description of the building is essential to the development of an appropriate flow network and to the representation of pressure distribution.

Building data requirements may be analysed in terms of

* flow path structure (number and distribution of flow paths and number of internal zones)

* flow characteristics of openings (flow coefficients)

* mechanical extract/supply data

* stack parameters (height of openings, internal air temperature distribution, description of flues and chimneys)

* wind pressure parameters (pressure coefficient data)

### 3.3.1 Flow Network

Ideally the location, size and flow characteristics of each opening should be defined. In practice, however, this is rarely possible and, instead, an approximation or an amalgamation of flow paths is almost always necessary. Consideration should first be given to penetrations within the building envelope; these govern the overall airtightness of the building and therefore the potential for air infiltration. In general it can be assumed that the larger the total area of openings, the greater will be the infiltration rate for any given set of external conditions. However, this relationship need not be linear and depends to some extent on the flow characteristics of each opening and on the distribution of openings. For accurate results it is essential that all sources of air infiltration are identified. These sources may be usefully analysed in terms of 'component' leakages, 'background' or 'fabric' leakages and large openings such as loading bay doors.

#### 3.3.1.1 Component Leakage Openings

Typical component openings include vents, stacks and chimneys. These represent the most straightforward type of building penetration to identify and include in the flow network description. Operable openings such as windows, doors and dampers also present little difficulty in terms of identification.

#### 3.3.1.2 'Background' or 'Fabric' Leakage Openings

Unfortunately identifiable sources of air leakage often represent only a small proportion of the total infiltration routes, with unidentifiable 'fabric' or 'background' penetrations accounting for the remainder. This 'background' component is attributable to construction techniques, site practices and the inadequate sealing of service penetrations, with the result that without careful design and construction it can have a dominating influence on the rate of air infiltration.

In terms of flow path development, the 'background' leakage may generally be assumed to be uniformly distributed about the surface area of the building and may therefore be represented in terms of 'leakage'/unit area of building envelope. Clearly this requires some judgement; for example, impermeable floors, roofs and party walls should be excluded from the envelope area. On the other hand air permeable ceilings beneath ventilated roof spaces should form part of the envelope area rather than the roof itself.

Since each face of the building is invariably subjected to differing wind pressures and since the stack effect influences the vertical pressure distribution on each face, 'background' leakage paths must be carefully selected to ensure that the combined influence of wind and stack action is adequately represented. In practice this means that 'background' flow paths should be defined for each face of the building at a minimum of two levels. For multi-storey buildings, especially those having an effectively impermeable barrier between each floor, flow paths should be specified at a minimum of two levels/faces/storeys.

An alternative method of distributing 'background' leakage components is to distribute the leakage according to the perimeter lengths of building joints; for example, the lengths of floor, wall and roof joints. This technique is especially useful for buildings constructed from a small number of relatively impermeable pre-fabricated elements.

### 3.3.1.3 Large Openings

Large openings such as factory loading bay doors require special attention since such openings may generally be expected to cross the neutral pressure plane. Therefore it is unlikely that unidirectional flow can be assumed and hence a single flow path representation would be inappropriate (Figure 3.14).

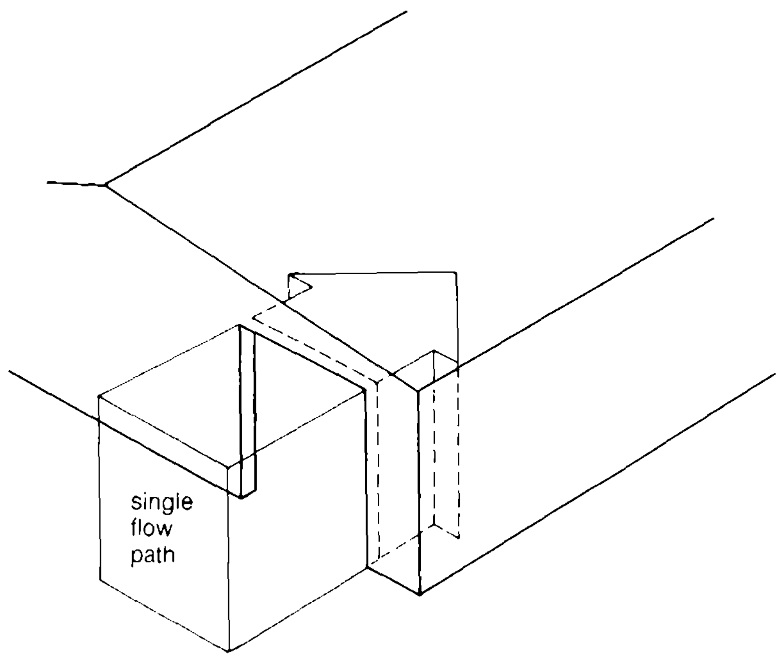


Figure 3.14 Single flow path representation of open door

One solution is to re-write the orifice flow equation as

$$Q_x = C_d A_x \left[ \frac{2}{\rho} \Delta p \right]^{\frac{1}{2}} \qquad (m^3/s) \qquad (3.42)$$

where $Q_x$ = flow through a horizontal strip of the door

If the open door is divided into y horizontal strips, then y vertically spaced flow paths may be defined to represent the total air flow through the door (Figure 3.15). Each flow path is then treated separately.

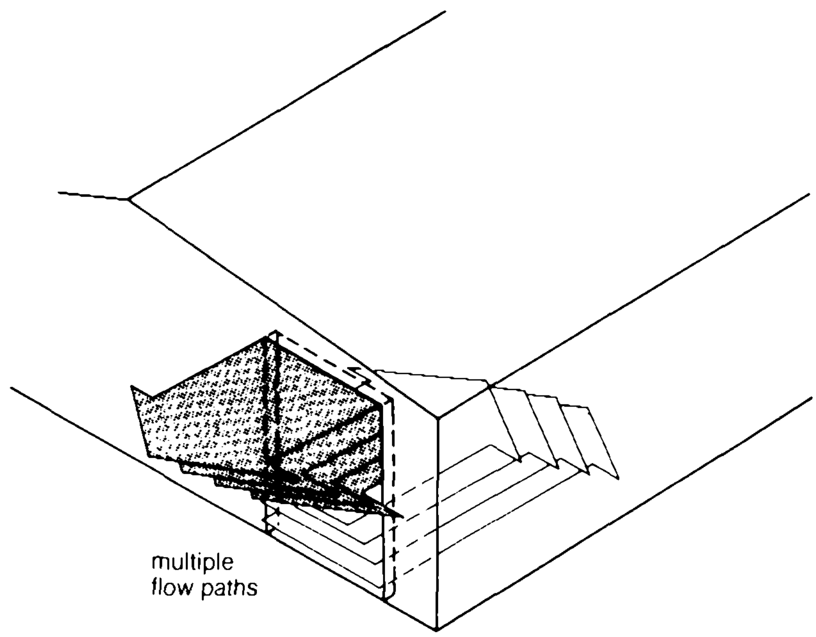


Figure 3.15 Multi flow path representation of open door

3.3.1.4 Interior Flow Paths

The interior flow network is developed in much the same way as the exterior network, concentrating on the room layout and inter-connecting flow paths. Typical routes are leaky internal doors, stairwells, lift shafts and ventilation ducting. External 'background' leakage paths will also require some adjustment in multi-zone flow networks to correspond to the exposed surface areas of individual rooms or zones (Figure 3.16).

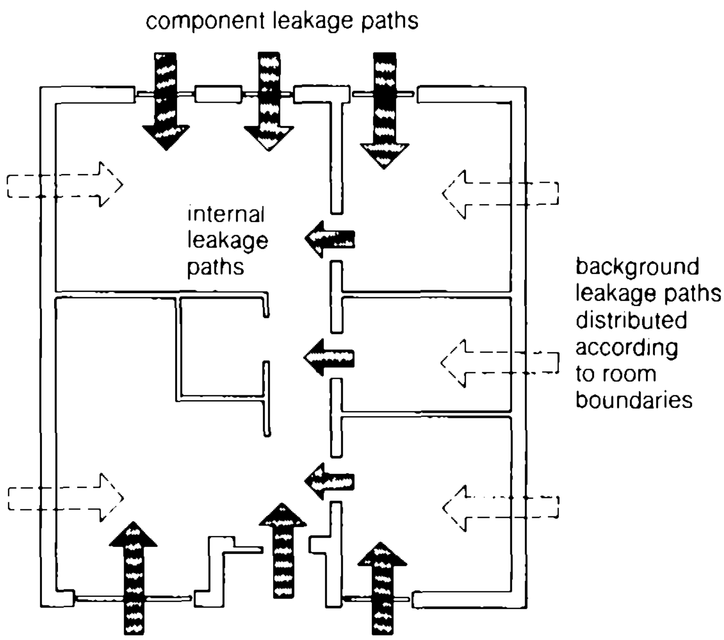


Figure 3.16 Multi zone flow path illustration (plan view)

### 3.3.2 Flow Characteristics of Openings

3.3.2.1 Numerical Description of Flow Characteristics

It is necessary to describe the flow characteristics of each of the defined flow paths. Sufficiently accurate estimates of the flow characteristics of purpose-provided openings, closed doors and windows may normally be determined by measuring the surface area of exposed openings and applying the appropriate orifice or duct flow equation (equations 3.1 and 3.4). Alternatively the data may be available from the manufacturer or, if applicable, by reference to the national standard covering the leakage performance of such openings. Additionally typical component leakage data and performance standards are detailed (Section 6.3).

Assessing the leakage characteristics of 'background' openings presents an altogether much less straightforward problem. By its very nature, this component of air infiltration is very variable and yet must be accurately represented. For many varieties of building and construction methods, a steadily increasing database of 'background' leakage data has become available and an attempt to summarise these data is included in Section 6.1 of the Data Reference Section. This task has been made easier by the introduction of airtightness standards in several countries, for certain categories of building, which place an upper limit on permissable 'fabric' leakage[16]. To meet these needs it has become necessary to develop proven airtightness construction techniques and suitable testing methods, both of which have assisted in the development of good design practices. Typical airtightness methods for dwellings are contained in the AIC's handbook 'Air Infiltration Control in Housing'[17].

At the building design stage it is recommended that the 'background' leakage characteristics most applicable to the building type and construction method proposed, should be applied using the data presented in Section 6.3. However, because the rate of air infiltration is critically dependent on the leakage performance of the building, design leakage should, wherever possible, be verified on completion of the building. Poor design or site practice can be expected to result in an adverse departure from the published leakage data.

3.3.2.2 The Measurement of Air Flow Characteristics

The measurement of air leakage itself is achieved using a suitably rated fan to create incremental pressure differences between the exterior and interior of the building in the ± 10-100 Pa range. For each pressure increment, the corresponding air flow rate through the fan is measured and the resultant air leakage characteristics plotted (Figure 3.17).

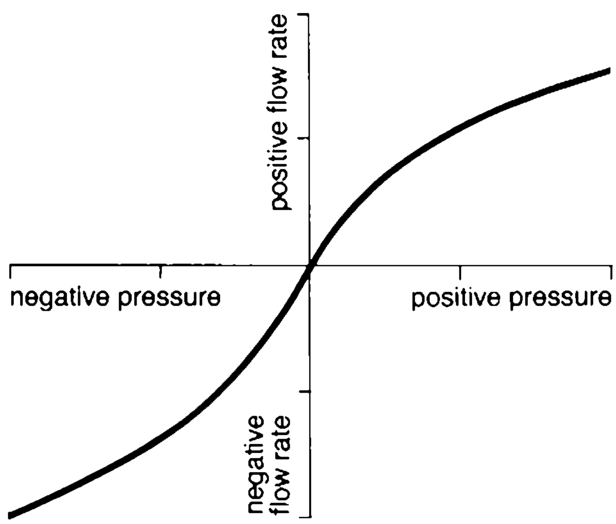


Figure 3.17 Air leakage characteristics plot

The flow coefficients (power law or quadratic) are determined by curve fitting. The pressure regime is selected such that it is above normal ambient pressures yet is not sufficient to force penetrations to open or close. For buildings of internal volumes up to 500 $m^3$ (single family dwellings or individual apartments) such testing is becoming common, using commercially available 'blower doors'.

These devices fit into a door opening without the need to remove the door, and enable a test to be performed rapidly. Similar methods, but using much larger fans, have been successfully employed in industrial buildings[18]. The same approach may also be used to determine the air leakage characteristics of commercial buildings although, frequently, a less costly alternative is to use the building's own air handling system[18].

### 3.3.3 Climatic and Terrain Data

Buildings of identical construction and air leakage performance will exhibit differing air infiltration patterns according to local climatic and terrain conditions. Climatic conditions vary widely according to location and season and as a result of the general random behaviour of weather. As a consequence it is not normally possible to predict hourly or even daily weather conditions and, instead, design approaches need to be based on historic weather records. Most commonly, average data, based on the results of many years of observation, are used. This approach has the advantage of ensuring that random extremes in climate are ignored. However, it suffers from the disadvantage of not being representative of an observed weather record. A more recent alternative is to consider an example weather[19,20] based on an hourly sequence of actual observations throughout a 12 month period where the sequence is selected to represent the least abnormal year from those for which data are available. The intention is that an identical weather database can be used for predictive techniques, thus ensuring the uniformity of comparisons between different designers. To conform with other building performance calculations, 'example weather year' data is recommended for infiltration design methods when available.

Whichever data option is selected, the climatic records are required from the most appropriate weather station within the locality of the building. These data should be available from the relevant national meteorological organisation listed in Section 6.1. Hourly climatic data is required and needs to be obtained in the form of a statistical relationship between wind speed and air temperature.

This format is necessary since air infiltration is a function of both of these climatic variables. Typical examples of these frequency distributions as supplied by the listed meteorlogical organisations are reproduced in Section 6.1. Similar tables are also available as a function of wind direction for use in instances in which infiltration rates are affected by wind direction.

The wind data supplied by meteorological organisations normally represent measurements made at a standard height of 10m in open flat country. These data must be corrected, using one of the methods described in Section 3.1.3.1. to compensate for both terrain roughness at the building location and for the difference between the wind speed measurement height and the wind pressure datum level (usually building height).

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## CHAPTER 4: Subsidiary Calculations

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### INTRODUCTION

The determination of the rate of air infiltration into buildings represents only a small part of the overall ventilation design need. Having satisfactorily predicted the infiltration performance of a building shell, it is necessary to determine the impact of air infiltration on both the building heat loss and on the desired ventilation strategy. In addition it is also necessary to ensure that ventilation needs will be satisfied and that internally-generated pollution is adequately controlled. The cost-effectiveness of design options of comparable performance must also be assessed.

The subsidiary calculations necessary to perform these tasks are presented in this chapter. The chapter begins with an analysis of the energy equation, followed by an outline of methods to calculate the cost-effectiveness of ventilation strategies. The calculation of indoor air quality aspects of ventilation design is then described.

### 4.1 HEAT RECOVERY

Heat recovery provides a method for recycling waste heat from the extract air supply of mechanical ventilation systems. This may be achieved by one of two methods. With an extract only ventilation system, a heat pump is used to absorb heat from the outgoing air. In large buildings this heat pump may be of the air-to-air variety, with the recycled heat being used for space heating.

In single family dwellings an air-to-water heat pump is normally the preferred option, with the absorbed heat being used to preheat the domestic hot water supply.

The common method of heat recovery for balanced supply/extract systems is to use an air-to-air heat exchanger. Heat recovered from the exhaust air is transferred to the supply air either by means of a thermal wheel or a 'plate' exchanger.

In both cases the overall efficiency of heat recovery is approximately 70%, although this can be reduced by the need to defrost the system.

Whether using heat pumps or heat exchangers, it should be noted that heat is only recovered from air passing through the exhaust air duct. Exfiltration losses are not included and therefore, if significant, will considerably affect the overall proportion of heat recovered from the total air mass leaving a building. This reduction in overall performance is illustrated in Figure 4.1.

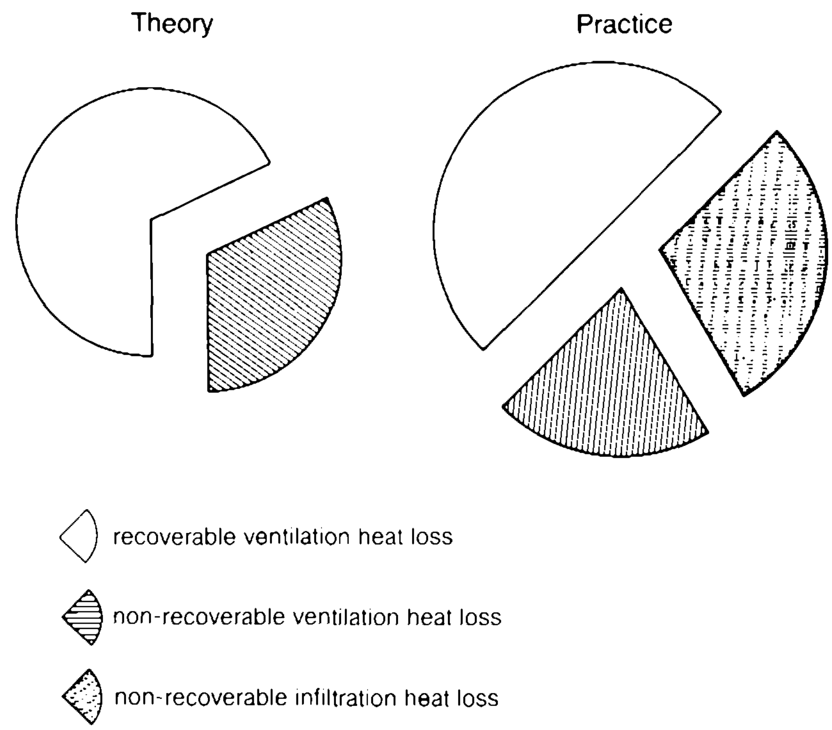


Figure 4.1 Comparison between theoretical and actual heat recovery performance

Figure 4.1(a) represents typical total heat recovery from a completely airtight building in which the ventilation rate is controlled by mechanical means. In practice residual air infiltration takes place, which increases the air change rate and therefore reduces the overall efficiency of heat recovery. The resultant increase in energy and reduction in heat recovery efficiency is depicted in Figure 4.1(b).

Heat recovery performance and the impact of airtightness are important parameters in establishing the viability of ventilation strategies; the equations covering this aspect of the design process are covered in the next two sections.

### 4.1.1 Heat Loss Calculation

Assuming the need to maintain the thermal environment of the interior of a building, then the required heat input necessary to compensate for the temperature differential between the incoming infiltrating air and the displaced exfiltrating air is given by

$$H = Q\rho c_p(T_{int} - T_{ext}) \quad (W) \qquad (4.1)$$

where
$Q$ = air flow rate ($m^3/s$)
$\rho$ = air density ($kg/m^3$)
$c_p$ = specific heat of air (J/kg/K)
$T_{int}$ = internal temperature (K)
$T_{ext}$ = external temperature (K)

If the air flow rate consists of components of mechanical ventilation $Q_{mv}$ and infiltration $Q_{inf}$, then the heat requirement becomes

$$H = (Q_{mv} + Q_{inf})\rho c_p(T_{int} - T_{ext}) \quad (W) \qquad (4.2)$$

### 4.1.2 Heat Recovery Calculation

Heat recovery is only possible from the mechanical ventilation portion of the total air flow. If the efficiency of the heat recovery system, $H_{eff}$, is defined as a percentage proportion of the heat recovered from that which is expelled by the ventilation system, then the overall ventilation heating requirement is given by

$$H = (Q_{inf} + Q_{mv}\{1 - H_{eff}/100\})\rho c_p(T_{int} - T_{ext}) \quad (J/s) \qquad (4.3)$$

This is an important equation since it illustrates that if the infiltration rate is comparable or greater than the mechanical ventilation rate, then efforts to introduce mechanical ventilation with heat recovery will not only be questionable from a capital cost point-of-view, but may also result in increased energy use. To ensure proper operating conditions

$$Q_{inf} << Q_{mv} \qquad (4.4)$$

## 4.2 COST-EFFECTIVENESS OF VENTILATION STRATEGIES

The fundamental design criterion for energy efficient ventilation is to minimise space heating and cooling loads while maintaining adequate indoor air quality. As a general rule, the selected approach must also be cost-effective. In this respect, the amount of energy conserved depends not only on an overall air change rate but also on the severity of the climate. Thus climate has an important influence on the choice of ventilation strategy. For example, in particularly severe climatic zones there is a much greater scope for conserving energy than in less severe locations; in those zones fairly elaborate design solutions can be contemplated.

Following the convention used in investigating other building heat loss mechanisms, the concept of degree days (Section 3.3.3) is used in this guide to assess the cost-effectiveness of ventilation strategies. Despite the lack of international uniformity regarding the definition of degree days, this concept provides a convenient method for defining an approximate 'climatic threshold' at which specific airtightness and ventilation approaches become cost-effective options.

The essential choice is between an almost totally airtight design in which separate provision is made to satisfy ventilation needs by mechanical means, or introducing airtightness measures such that natural ventilation is sufficient to meet most needs. While the former technique offers good control over air change rates, and hence provides an opportunity to benefit from the full value of air infiltration reduction techniques, its main disadvantages are that system expense and additional construction costs are high. Furthermore, it is essential that the design airtightness is maintained throughout the life of the building. By comparison, the partial airtightness approach, incorporating natural ventilation, involves a much smaller increase in capital costs. In addition, a margin of natural leakage ensures a certain degree of safety, while at the same time excessive rates of air infiltration are minimised. However, the latter technique does not offer the same degree of energy conservation as the former. The conditions under which these alternative approaches become financially worthwhile are covered in the next section.

### 4.2.1 Conditions for Cost-Effectiveness of Ventilation Strategies

The installation and operation of a ventilation system adds to building costs. Costs include:

* initial capital expenditure on purchase and installation

* operating costs

* general maintenance charges

Where alternative strategies are feasible, a comparative 'pay back' period may be defined such that, over a given period of time, a system which, perhaps, incurred a greater initial expenditure will prove to be less expensive than a much cheaper system incurring a higher overall operating cost. A typical example is the choice between mechanical ventilation with heat recovery, and natural ventilation. To be cost-effective, the annual energy saving of a ventilation approach must outweigh its combined operating and payback cost.

For the analysis to be accurate, it should also focus on inflationary factors. However, as energy prices tend to rise in line with or above the rate of inflation, a straightforward analysis at current costs may be expected to provide sufficient information. The potential for the cost-effectiveness of alternative ventilation strategies will depend on the scope of energy reductions. In turn, this is a function of the overall ventilation rate and the severity of climate. Thus, for a specific application, a cost-effective measure in one locality may not necessarily prove a satisfactory option somewhere else.

In energy investigations, the severity of climate is frequently quantified in terms of degree days, where a degree day is the number of degrees of temperature difference on any one day between a given base temperature and the corresponding daily mean outside air temperature. Unfortunately, there is no international agreement on base temperature, although it is normally regarded as the external temperature below which space heating is required. Typical values of both base temperature and design indoor temperature for buildings are summarised in Section 6.1.

Differences between design room temperature and the temperature at which heating is needed are assumed to be satisfied by incidental gains from solar radiation, building components, and powered appliances, etc. In the United States the concept of degree days is also used for cooling-load calculations where the cooling degree day is based on the number of degrees above a base temperature of $25^{o}C$. This approach additionally incorporates the specific enthalpy of outside air to accommodate the need to condition the interior humidity of the building. The heating and cooling load degree days are summed algebraically to give an 'infiltration' degree day (IDD) for use in air infiltration calculations[1].

Where degree day base temperatures correspond to the threshold temperature at which space heating is required, the annual ventilation space heating demand is given by

$$E = Q \times DD \times 24 \times 3600 \rho S \times 10^{-9} \quad (GJ) \qquad (4.5)$$

where $Q$ = ventilation/infiltration flow rate ($m^3/s$)

$DD$ = number of degree days

$\rho$ = air density $\simeq$ 1.21 $kg/m^3$

$S$ = specific heat of incoming air $\simeq$ 1012 J/Kg

In terms of hourly air change rate, this equation becomes

$$E = \frac{ACR \times Vol \times DD \times .1058}{3600} \quad (GJ) \qquad (4.6)$$

where $ACR$ = hourly air change rate ($h^{-1}$)

$Vol$ = volume of heated space ($m^3$)

Where published degree day data cannot be equated with the heating threshold, then it must be first recalculated to an appropriate base[2].

The above representation of annual energy requirement enables a very approximate assessment of the cost-effectiveness of alternative ventilation strategies and airtightness measures to be determined. It is valid provided that continuous, uniform space heating is applied throughout the building. Should the period over which heating is applied each day be reduced (eg night set-back), or should parts of the building be operated at a lower temperature, then there will be a corresponding reduction in heating load and a consequent reduction in overall energy consumption. This will tend to lengthen payback periods. An example comparing the relative cost performances of a mechanical and natural ventilation system is presented in Section 5.2.

## 4.3 INDOOR AIR QUALITY

There are two indoor air quality related aspects of ventilation design which may be analysed using air infiltration modelling techniques. The first concerns the ingress or re-entry of polluted air as a result of back-draughting and the second concerns the relationship between the pattern of ventilation and the concentration of internally-generated pollution.

### 4.3.1 Back-draughting

Back-draughting and the cross-contamination of pollution from one zone to another occurs largely as a result of poor design. The problem arises when air outlets, such as chimneys - intended for the direct removal of pollution - become supply points. The culprit is often mechanical extract ventilation which is capable of developing large negative pressures within a building and therefore acts against the natural draughting effect (stack effect) of chimneys (Figure 4.2).

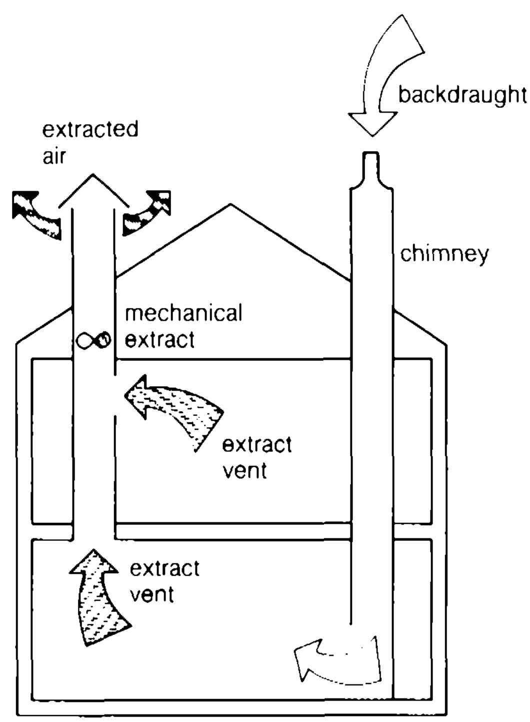


Figure 4.2 Condition for back draughting

The installation of piecemeal or uncoordinated ventilation approaches in particular can cause this problem. Back-draughting may also occur in naturally ventilated buildings during periods of adverse weather conditions, or if purpose-provided openings become blocked, or if stacks and chimneys terminate above the building in positive pressure regions.

Analysis of the problem is very straightforward, since back-draughting and cross-contamination problems may normally be identified by an analysis of the internal pressure distribution. Thus, air entry paths may be immediately identified and checked for the possibility of back-draughting or cross-contamination, without the need to undertake extensive calculations. Since mechanical extract ventilation will generally be the dominant driving force, the underpressure is given by

$$(\Delta p_{mv})^n = \frac{Q_{mv}}{K_t} \qquad (4.7)$$

where $Q_{mv}$ = mechanical ventilation rate ($m^3/s$)

$K_t$ = flow coefficient for building

$n$ = flow exponent for building

$\Delta p_{mv}$ = induced pressure due to mechanical ventilation (Pa)

To check for problems, this pressure must be compared with those acting on exhaust points (eg flues and chimneys).

### 4.3.2 Pollutant Concentration and Minimum Ventilation Rates

The minimum fresh air supply necessary to meet respiratory needs is estimated to vary between 0.1 - 0.9 $dm^3/s$/person depending on the intensity of activity. Much higher rates of ventilation are required to maintain adequate indoor air quality and it is this problem which normally dictates overall ventilation needs. There is a direct link between modern airtightness practices and poor indoor air quality with the result that minimum ventilation studies have become inextricably linked to air infiltration and airtightness investigations. It is important therefore that design methods introduced to minimise ventilation heat loss should not conflict with the need to supply sufficient fresh air to dilute and disperse internally-generated pollution.

There are several common pollutants, each of which can cause discomfort or are harmful to building occupants. Following the work of Yaglou[3], ventilation requirements in the past have frequently concentrated on minimising the intensity of odour. In addition, moisture has also been a major source of concern and in many instances has presented a much more serious problem. Other ventilation requirements have focussed on combustion needs and on the dispersal of combustion products. Again, poor ventilation design may result in incomplete burning or in the back-draughting of toxic gases into occupied zones.

More recently, anxiety has grown over gaseous and particle emissions from building materials. In the forefront has been formaldehyde emission from both particle boards and wall thermal insulation. The radioactive decay products of radon gas, emitted from certain varieties of gypsum plaster board and from underlying strata, is also under intensive research.

Among the less common pollutants are the diverse range of chemicals in industrial buildings and airborne bacteriological contamination found in hospitals. Each of these sources demands adequate ventilation to prevent toxic build-up or cross-contamination.

In general, each pollutant requires a different ventilation rate to ensure sufficient dilution and removal. These rates are primarily dependent on:

* source and strength of the pollutant
* external concentrations
* discomfort effects
* toxicity

As a rule, the minimum prescribed ventilation rate must at all times exceed the rate necessary to disperse the pollutant requiring most ventilation. When more than one source contributes to the emission of a single pollutant, the ventilation rates needed to satisfy the requirement of each source are summed to obtain the total rate.

Subject to the condition of uniform mixing of pollutants within each cell or zone of the building and provided that sources and emission rates of pollutants can be estimated with some degree of accuracy, then air infiltration models may be used to estimate the time-varying concentration of these pollutants.

The concentration of a contaminant in a leaky enclosure is given at any instant in time by the continuity equation

$$\underbrace{\frac{Vol \times dC_{in}}{dt}}_{\text{Term 1}} + \underbrace{mQ\,(C_{ext} - C_{in})}_{\text{Term 2}} = \underbrace{(S - \lambda)}_{\text{Term 3}} \quad (\text{mass/time}) \qquad (4.8)$$

where Vol = volume of enclosure ($m^3$)

$\lambda$ = rate of chemical or physical decay of pollutant (mass/s)

$m$ = empirical mixing factor (varies from 0 to 1, m=1 is equivalent to perfect mixing)

$C_{in}$ = internal concentration of pollutant (mass/$m^3$)

$C_{ext}$ = external concentration of pollutant (mass/$m^3$)

$Q$ = ventilation rate ($m^3/s$)

$S$ = total rate of emission of pollutant (from all sources)

The above equation may be solved when any six of the seven parameters are known and, in practice, a solution is normally made possible by eliminating some parameters altogether. Two formulations of the continuity equation may be readily analysed and will enable approximate pollution concentrations to be determined for many situations. The first considers the constant emission of a pollutant, for example the emission of formaldehyde or radon within a building.

Assuming a steady state air exchange rate, the internal concentration of pollutant will eventually reach equilibrium. Thus term 1 of equation 4.8 will tend to zero and the equilibrium concentration will be given by

$$(C_{int} - C_{ext}) = \frac{(S - \lambda)}{mQ} \tag{4.9}$$

In the case of formaldehyde, there will be no physical or chemical degradation, neither will there be an external component. Therefore both $\lambda$ and $C_{ext}$ are equal to zero. If perfect mixing is assumed (m=1) the internal equilibrium concentration becomes

$$C_{in} = \frac{S}{Q} \tag{4.10}$$

Radon experiences physical delay, hence

$$C_{in} = \frac{S - \lambda}{Q} \tag{4.11}$$

where $\lambda$ = decay rate

Once the emission of a pollutant ceases, the emission rate, S, becomes zero and the pollutant concentration decays as a function of time. Eliminating term 3 from equation (4.8) and integrating yields

$$C_t = C_{t_o} e^{-Q/vt} \qquad (4.12)$$

where $C_t$ = pollution concentration at time (t) after cessation of pollutant emission ($t_o$)

$C_{t_o}$ = equilibrium pollutant concentration

Therefore, by calculating air change rates and by making assumptions regarding the emission of pollutants, it is possible to use the results of air infiltration models to predict possible indoor air quality problems.

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## CHAPTER 5: Algorithms and Worked Examples

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### 5.1 ALGORITHMS

This section describes the essential elements of three published algorithms which are freely available and will, between them, enable the design calculations covered in this applications guide to be performed. Two of the models to be described were included in the AIVC's programme of model validation[1] while the third is of more recent origin and is intended as an algorithm for inclusion in a dynamic heat model. The specific models are

1. Lawrence Berkeley Model for calculating air infiltration using Equivalent Leakage Area data[2]

2. National Bureau of Standards Algorithm for estimating infiltration and inter room air flows[3]

3. National Research Council of Canada Model for calculating air infiltration in buildings[4]

The first model is of the single zone variety. The second two models are variants of the multi zone technique.

#### 5.1.1 Lawrence Berkeley Laboratory Equivalent Leakage Area (ELA) Algorithm

The concepts of this algorithm are outlined in Section 3.2.3. It was developed to predict the impact on air infiltration rates of retrofit and other changes in the building envelope using the minimum number of model parameters. The technique was specifically designed for simplicity and therefore precise detail has been sacrificed for ease of application. Model parameters include

* leakage of structure (as inferred by building pressurization or by reference to the characteristic leakage performance of individual building components (Section 6.3).

* ratio of floor/ceiling leakage to wall leakage
* height of building
* internal/external temperature difference
* wind speed
* terrain class (Table 6.2.8, Chapter 6)
* shielding class (Table 6.2.9, Chapter 6)

) to determine external pressure distribution

The primary feature of this approach is that the calculation is split into two distinct components, these being the separate calculation of wind infiltration and stack infiltration. Infiltration in these two regimes is expressed by

$$Q_w = f_w^* A_o V' \tag{5.1}$$

$$Q_s = f_s^* A_o (\Delta T)^{\frac{1}{2}} \tag{5.2}$$

respectively, where

$A_o$ = the equivalent leakage area of the structure ($m^2$)

$Q_w$ = the infiltration in the wind-regime ($m^3/s$)

$Q_s$ = the infiltration in the stack regime ($m^3/s$)

$f_w^*$ = the 'reduced' wind parameter

$f_s^*$ = the 'reduced' stack parameter ($m/s.K^{\frac{1}{2}}$)

$V'$ = the (weather tower) wind speed (m/s)

$\Delta T$ = inside/outside temperature difference (K)

The value of equivalent leakage area, $A_o$, is given by

$$A_o = \frac{K_t(\Delta p_{ref})^n}{(\frac{2}{\rho}\Delta p_{ref})^{\frac{1}{2}}} \quad (m^2) \tag{5.3}$$

where K = total flow coefficient for building ) determined by pressurization

n = flow exponent ) determined by pressurization

$P_{ref}$ is a reference pressure difference for calculating the equivalent leakage area and has been arbitrarily chosen to be equal to 4 Pa, i.e.

$$A_o = \frac{K_t(4)^n}{(\frac{8}{\rho})^{\frac{1}{2}}} \quad (m^2) \tag{5.4}$$

The reduced wind parameter, $f_w^*$, is given by the following expression

$$f_w^* = C' \left[ (1-R)^{1/3} \right] \left[ \frac{\alpha \left[\frac{H}{10}\right]^{\gamma}}{\alpha' \left[\frac{H'}{10}\right]^{\gamma'}} \right] \qquad (5.5)$$

where

| | | | |
|---|---|---|---|
| $C'$ | = | the generalised shielding coefficient | see Tables 6.2.8 and 6.2.9 |
| $R$ | = | the vertical leakage fraction, i.e. the fraction of leakage in the floor and ceiling | |
| $\alpha, \gamma$ | = | on-site terrain parameters | |
| $\alpha', \gamma'$ | = | off-site terrain parameters | |
| $H$ | = | height of the structure (m) | |
| $H'$ | = | height of the wind measurement (m) | |

and the reduced stack parameter, $f_s^*$, is given by

$$f_s^* = \frac{(1 + R/2)}{3} \left[ 1 - \frac{X^2}{(2 - R)^2} \right]^{3/2} \sqrt{\frac{gH}{T}} \qquad (5.6)$$

where

$X = \dfrac{A_{ceiling} - A_{floor}}{A_o}$ is the ceiling-floor leakage difference

$g$ = the acceleration of gravity (9.81 m/s)

$T$ = the inside temperature

Infiltration is given by summing the wind and stack components in quadrature (Chapter 3) to give

$$Q_{inf} = (Q_w^{\ 2} + Q_s^{\ 2})^{\frac{1}{2}} \qquad (5.7)$$

Data requirements:
- air leakage (pressurization) test data
- internal/external air temperature
- wind speed data
- terrain and shielding conditions
- building information (vertical/horizontal distribution of openings)

The main advantage of this method is that the wind and stack infiltration equations may be readily evaluated. However, this approach does suffer from a number of disadvantages which limit its further applicability. Its main disadvantage is that the leakage distribution is divided into horizontal and vertical components only. No allowance is made for non linear leakage distribution, such as that caused by open doors, therefore the effects of such openings cannot be modelled. For similar reasons, it is also not possible to establish the flow routes into the zone or to determine the direction of flow, therefore the method is unsuitable for air movement and indoor air quality studies.

### 5.1.2 National Bureau of Standards Model[3]

This is a comprehensive multi-zone model with a published annotated FORTRAN IV listing. In addition to being capable of calculating infiltration and inter-room air flow rates, this algorithm interfaces with the NBS dynamic heat model, TARP (Thermal Analysis Research Program)[5].

Air flow through each opening is based on the exponential form of the flow equation, given by

$$Q = \rho k(\Delta p)^n \qquad \text{(kg/s)} \qquad (5.8)$$

where
$k$ = flow coefficient
$n$ = flow exponent
$\rho$ = air density

However, in the algorithm, the flow constant k is represented by an area of an opening based on the orifice equation, i.e.

$$Q = C_d A.\rho\left(\frac{2}{\rho}\Delta p\right)^{\frac{1}{2}} \qquad \text{(kg/s)} \qquad (5.9)$$

where
$C_d$ = discharge coefficient
$A$ = area of opening

The exponent n remains unaltered.

Provision is made to express the stack pressure for both internal and external openings. Also air temperature is specified for each zone, thus enabling inter-zone temperature differences to be included in the stack pressure calculation. Wind pressure data is inferred from wind velocity measurements and is automatically calculated for each face of the building and for any wind direction. However, as presented, the empirical routine used for calculating wind pressure makes no allowance for different levels of wind shielding.

Mechanical ventilation is entered as a constant value in each zone to which it applies.

Stack induced two-way flow through large openings is also included in the algorithm by dividing such openings into two segments.

Input requirements for each zone include:

* zone number
* zone height (m)
* zone temperature ($^{o}$C)
* mechanical ventilation rate ($m^3s$)

The additional input data for each flow path includes:

* flow path originating zone number
* flow path terminating zone number (outside = zero)
* area of opening (calculated from mass flow coefficient)
* flow exponent
* discharge coefficient (see equation)
* azimuth angle
* height of opening (m)
* ceiling height (m)

Basic climatic requirements cover:

* external air temperature ($^{o}$C)
* wind speed (m/s)
* wind direction ($^{o}$)

Since calculations are concerned with predicting mass flow rates of air for the purpose of determining heat loss, volumetric air change rates are not included in the current version of this algorithm. However, by providing zonal and building volume data, the mass flow rates may be easily converted to air change rates. Single zone simulations may be performed by specifying one zone only.

The solution of the flow equations to achieve mass flow balance is performed using iterative techniques based on the Newton method. The processing time for each iteration is proportional to the cube of the number of flow paths and the number of iterations is directly proportional to the number of zones. Therefore, to minimise computation time, it is important to restrict the size of the flow network whenever possible.

### 5.1.3 National Research Council of Canada Model[4]

The purpose of this model is to calculate the air flows and pressure differentials that occur in a building as a result of a combination of wind effect, stack action and the operation of air handling systems.

The computer system is written in FORTRAN IV and is currently available in Imperial units only. A full listing of this program is published in the cited reference.

The building is represented by a series of vertically stacked compartments interconnected by vertical shafts. Each shaft is terminated by two vents which may be located at any desired floor level. Leakage openings are specified for each external wall and for all floors and shaft walls, thus enabling air to pass from every compartment or zone to adjacent zones and to each of the vertical shafts. In order to reduce computing time, each zone may represent a number of building storeys. The equation defining flow through each opening is given in exponent form.

The model assumptions and limitations are that

* friction resistance of vertical shafts is neglected
* net air supplied by the air handling system is assumed to be constant and independent of building pressures
* each component has an open plan with no provision for separate rooms or vestibules
* pressures, flows and leakage openings are assumed to occur at the mid-height of each level
* temperatures inside each compartment and shaft are assumed to be constant at 75°F (24°C).

Input requirements include

* flow coefficient and flow exponent for each flow path
* number of floors
* distance between floors
* number of shafts

* location of openings

* wind pressure (inferred from wind speed data)

* external temperature

A constant internal air temperature of 24°C is assumed and therefore, for other temperatures, the external air temperature must be modified to ensure that the temperature difference between the inside and outside of the building is correct. The assumption of a uniform internal temperature also rules out consideration of zonal temperature differences or linear temperature gradients. Despite these limitations, this model provides a good opportunity for analysing the infiltration characteristics and the performance of ventilation systems in open plan office buildings and dwellings.

## 5.2 EXAMPLES

### 5.2.1 Calculation of wind and stack pressure

A low rise building of height 7.5m with roof pitch angle of 22° and length to width ratio of 2:1 is situated

(a) in open countryside with no surrounding obstructions, and

(b) in an urban environment surrounded with obstructions of equal height

Wind speed measurements are made at a nearby open countryside weather station at a height above ground level of 10m.

For each exposure condition, determine

(i) The "wind reduction factor" necessary to convert the weather station wind speed to roof height wind speed.

(ii) The wind pressure coefficient for each face of the building and the roof, assuming that wind is normal to the long face of the building.

(iii) The roof height wind speed given measured values at the weather station of 1, 2, 5 and 10 m/s.

(iv) The corresponding wind pressure values.

(v) The stack pressure for openings spaced a vertical distance of 5 metres apart given temperature differences of 0, 10, 20, 30 and 40 K.

Solution:

(i) Wind reduction factor

Referring to Table 6.2.7, the terrain constants are:

| | K | a |
|---|---|---|
| open countryside | 0.68 | 0.17 |
| urban | 0.35 | 0.25 |

Roof height is 7.5m

∴ Wind reduction factors are:

open countryside $0.68 \times 7.5^{0.17} = 0.96$
urban $0.35 \times 7.5^{0.25} = 0.58$

The wind speeds measured at the meteorological station are multiplied by these factors to obtain the roof height wind speed for open countryside and urban terrain respectively.

(ii) Wind pressure coefficient

| | (Face (2:1) | | | | Roof | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | Front | Rear |
| Open countryside (Table 6.2.4) | 0.5 | -0.7 | -0.9 | -0.9 | -0.7 | -0.5 |
| Urban (Table 6.2.6) | 0.06 | -0.3 | -0.3 | -0.3 | -0.49 | -0.4 |

(iii) Roof height wind speed

Roof height wind speed is given by the meteorological wind speed multiplied by the wind reduction factor, i.e.

| Meteorological | Open Countryside | | Urban | |
|---|---|---|---|---|
| Wind speed (m/s) | Wind reduction factor | Roof height wind speed (m/s) | Wind reduction factor | Roof height wind speed (m/s) |
| 1 | 0.96 | 0.96 | 0.58 | 0.58 |
| 2 | 0.96 | 1.92 | 0.58 | 1.16 |
| 5 | 0.96 | 4.8 | 0.58 | 2.9 |
| 10 | 0.96 | 9.6 | 0.58 | 5.8 |

### (iv) Wind pressure values

The wind pressure is given by

$$P_w = \frac{\rho}{2} C_p V^2 \quad \text{(see equation 3.6)}$$

(Let air density $\rho = 1.29\ kg/m^3$)

Thus for open countryside

| Meteorological wind speed | Roof height wind speed | Wind Pressure (Pa) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Face | | | | Roof | |
| (m/s) | (m/s) | 1 | 2 | 3 | 4 | Front | Rear |
| 1 | 0.96 | 0.3 | - 0.4 | - 0.5 | - 0.5 | - 0.4 | - 0.3 |
| 2 | 1.92 | 1.2 | - 1.7 | - 2.1 | - 2.1 | - 1.7 | - 1.2 |
| 5 | 4.8 | 7.4 | -10.4 | -13.4 | -13.4 | -10.4 | - 7.4 |
| 10 | 9.6 | 29.7 | -41.6 | -53.5 | -53.5 | -41.6 | -29.7 |

and for urban terrain

| Meteorological wind speed | Roof height wind speed | Wind Pressure (Pa) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Face | | | | Roof | |
| (m/s) | (m/s) | 1 | 2 | 3 | 4 | Front | Rear |
| 1 | 0.96 | 0.04 | - 0.2 | - 0.2 | - 0.2 | - 0.3 | - 0.2 |
| 2 | 1.92 | 0.14 | - 0.7 | - 0.7 | - 0.7 | - 1.2 | - 1.0 |
| 5 | 4.8 | 0.89 | - 4.5 | - 4.5 | - 4.5 | - 7.3 | - 5.9 |
| 10 | 9.6 | 3.6 | -17.8 | -17.8 | -17.8 | -29.1 | -23.8 |

### (v) Stack pressure

$$\text{Stack pressure} = -\rho_o g 273(h_2 - h_1)\left(\frac{1}{T_{ext}} - \frac{1}{T_{int}}\right) \quad \text{(equation 3.12)}$$

Let $\rho_o = 1.29\ kg/m^3$

$g = 9.81\ m/s^2$

$h_1 = 0m$

$h_2 = 5m$

$T_{int} = 293K\ (20^oC)$

∴ The stack pressure at $h_2$ relative to $h_1$ is

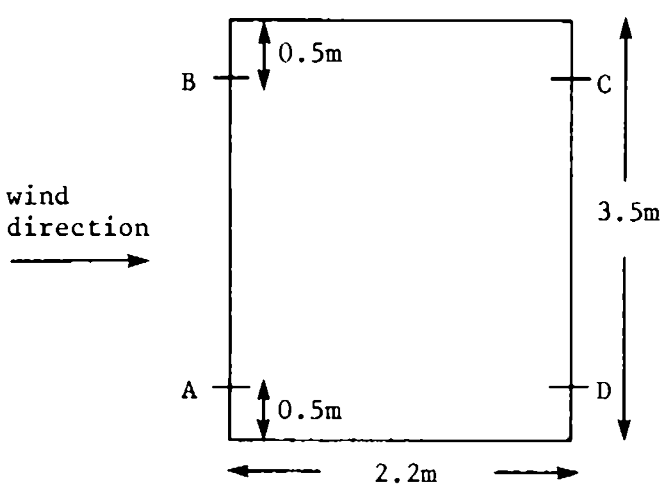
| Inside/Outside Temperature Difference (K) | Stack Pressure (Pa) |
|---|---|
| 0 | 0 |
| 10 | -2.1 |
| 20 | -4.3 |
| 30 | -6.7 |
| 40 | -9.3 |

This example illustrates the need to consider local shielding in the wind pressure calculation and also the significance of stack pressure, even for relatively small vertical distances between openings.

### 5.2.2 Distribution of Openings

An airtight structure of height 3.5m, width 2.2m and length 2.2m has orifice openings of 60 $cm^2$ centred at a height above base of 0.5 and 3.0 metres on both the front and rear faces (see illustration below). Assuming an open countryside location, a roof height wind speed of 1.5m and an internal/external temperature difference of 20°C, calculate the air change rates for the following configurations.

| Configuration | Opening (refer to sketch) | | | |
|---|---|---|---|---|
| | A | B | C | D |
| (i) | open | open | closed | closed |
| (ii) | open | closed | closed | open |
| (iii) | closed | open | closed | open |
| (iv) | open | closed | open | closed |




Points A, B, C, D represent location of orifice openings of size $60m^2$

Solution:

Using the approach outlined in the previous example, and by referring to Table 6.2.1, the wind, stack and total pressure acting on each opening are as follows:

| Opening | Stack Pressure (Pa) | Wind Pressure (Pa) | Total Pressure (Pa) |
|---|---|---|---|
| A | 0 | 1.02 | 1.02 |
| B | -2.16 | 1.02 | -1.14 |
| C | -2.16 | -0.29 | -2.45 |
| D | 0 | -0.29 | -0.29 |

By applying equation 3.28 to the total pressure calculated for each opening, the approximate internal pressure to give mass/flow balance, the infiltration rate and air change rate for each configuration are as follows:

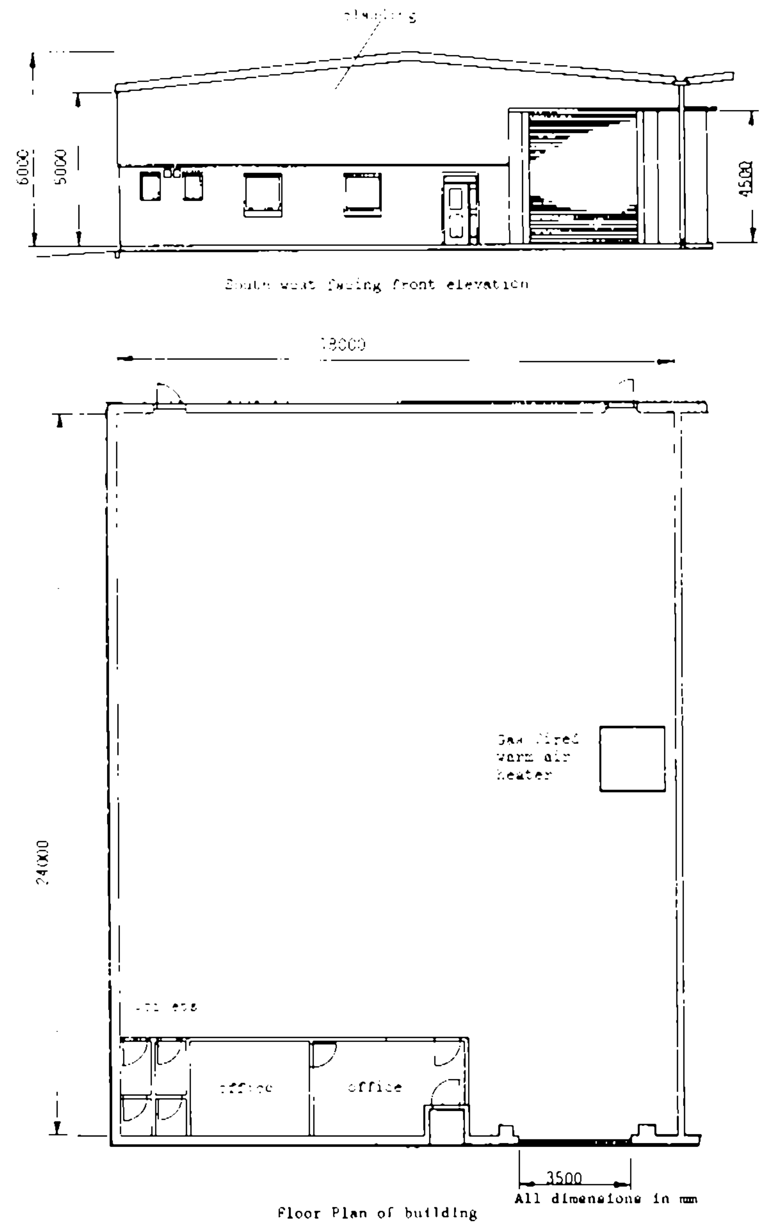
| Configuration | Internal Pressure ($P_{int}$) | Infiltration Rate ($dm^3/s$) | Air Change Rate ($h^{-1}$) |
|---|---|---|---|
| (i) | -0.06 | 4.7 | 1.0 |
| (ii) | 0.37 | 3.7 | 0.8 |
| (iii) | -0.72 | 3.0 | 0.6 |
| (iv) | -0.72 | 6.0 | 1.3 |

This example illustrates the strong dependence of the location of openings on the rate of infiltration.

### 5.2.3 Industrial Building

An industrial warehouse of internal volume of 2376 $m^3$ and overall dimensions of 24 x 18 x 6m is situated in urban surroundings, adjacent to buildings of similar height. Basic design details and orientation are illustrated in Figure 5.2.1. Located at the front of the building is a roller shutter loading bay door of dimensions 4.5 x 3.5m, an entrance door and two adjacent unweatherstripped windows. At the rear of the building are two further entrance doors. The building is constructed to a height of approximately 2.5m with 260mm unfilled brick cavity wall, while the upper section comprises insulated corrugated steel cladding. The roof is constructed of corrugated aggregate panelling.

Figure 5.2.1 Industrial building




(i) Devise a flow network using the leakage data presented in Chapter 6.3.

(ii) Determine the infiltration characteristics for the building over the external/internal temperature range of 0-30K and the meteorological wind range of 0-10 m/s (loading bay door closed).

(iii) For wind directed towards the front of the building, calculate the infiltration rate and air flow patterns at $\Delta T$ = 20K and a site wind speed at roof height of 0 and 60 m/s, assuming a fully open loading bay door.

Solution:

The leakage characteristics as determined from Chapter 6, Section 3 are presented in Table 5.2.1.

The corresponding infiltration characteristics and flow pattern through the door have been determined using the principles outlined in the previous examples and are illustrated in Figures 5.2.2 and 5.2.3 respectively.

Figure 5.2.2 Infiltration characteristics - industrial building

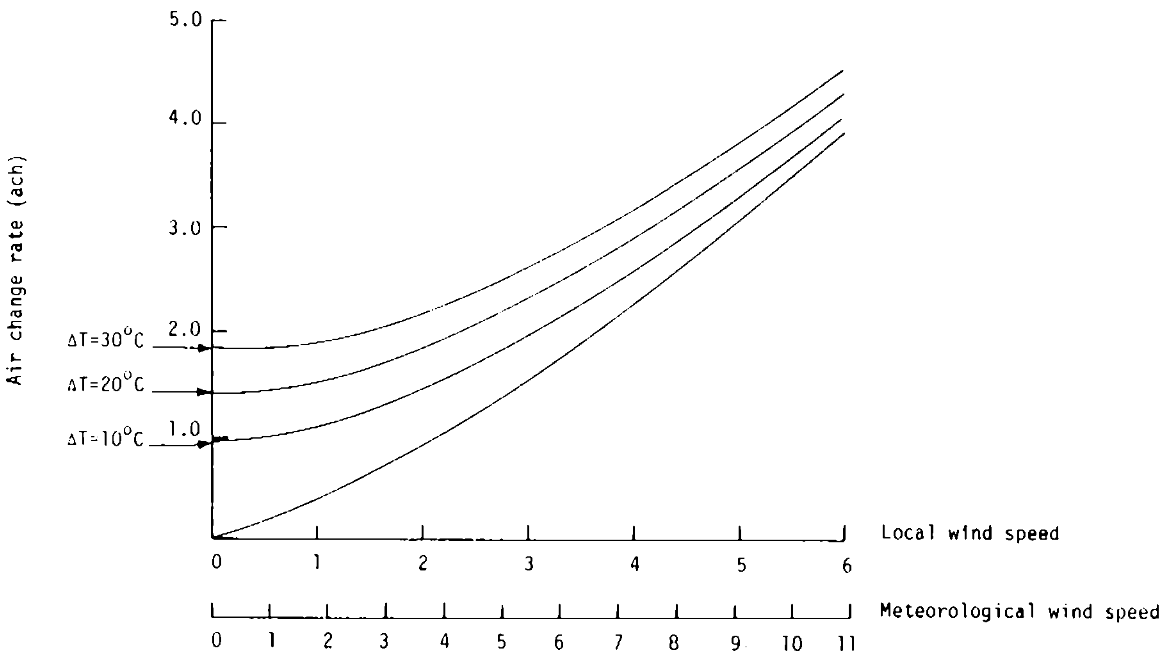
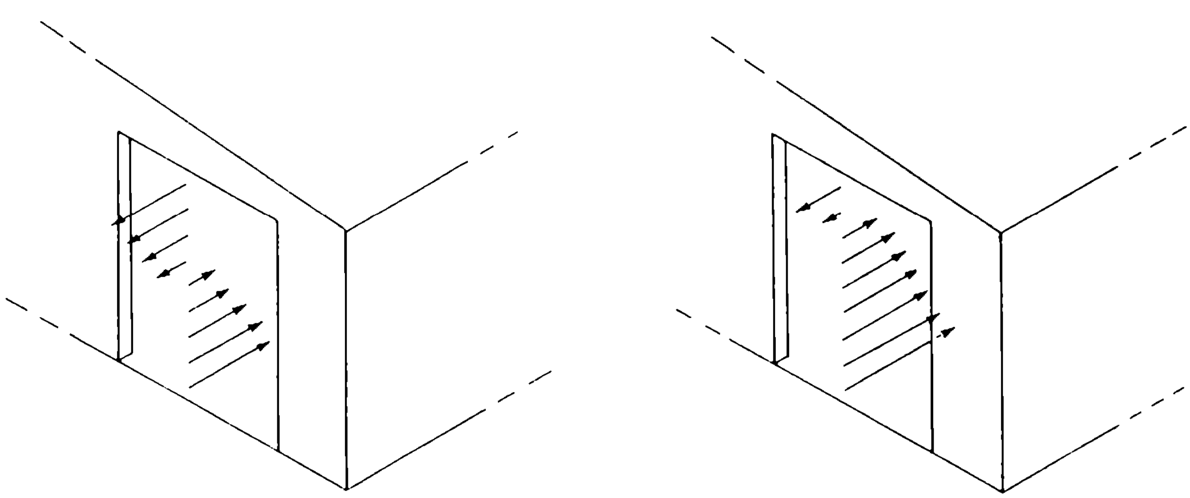



Figure 5.2.3 Air flow through doors



(a) $\Delta T = 20^{\circ}C$
Wind speed = 0 m/s

(b) $\Delta T = 20^{\circ}C$
Wind speed = 6 m/s

TABLE 5.2.1 Leakage characteristics

| Component | Length (or area of component) m (or $m^2$) | Unit flow coefficient $dm^3/s.m.$ Pa (or $dm^3/s.m^2\ Pa^n$) | Total flow coefficient $dm^3/s.Pa^n$ | Flow exponent | Data Reference Table (see Chapter 6) |
|---|---|---|---|---|---|
| Roof: | | | | | |
| Front | $216m^2$ | 0.64 | 138 | 0.67 | |
| Rear | $216m^2$ | 0.64 | 138 | 0.67 | |
| Brick - unfilled cavity | | | | | |
| Front | $45m^2$ | 0.18 | 8.1 | 0.8 | |
| Rear | $45m^2$ | 0.18 | 8.1 | 0.8 | |
| Side (left) | $60m^2$ | 0.18 | 10.8 | 0.8 | |
| Side (right) | $60m^2$ | 0.18 | 10.8 | 0.8 | |
| Steel cladding - insulated steel | | | | | |
| Front | $54m^2$ | 0.26 | 14.0 | 0.75 | |
| Rear | $54m^2$ | 0.26 | 14.0 | 0.75 | |
| Side (left) | $60m^2$ | 0.26 | 15.6 | 0.75 | |
| Side (right) | $60m^2$ | 0.26 | 15.6 | 0.75 | |
| Floor/wall joint - uncaulked | | | | | |
| Front | 18m | 1.5 | 27 | 0.5 | |
| Rear | 18m | 1.5 | 27 | 0.5 | |
| Side (left) | 24m | 1.5 | 36 | 0.5 | |
| Side (right) | 24m | 1.5 | 36 | 0.5 | |
| Brick/cladding joint - uncaulked | | | | | |
| Front | 18m | 1.5 | 27 | 0.5 | |
| Rear | 18m | 1.5 | 27 | 0.5 | |
| Side (left) | 24m | 1.5 | 36 | 0.5 | |
| Side (right) | 24m | 1.5 | 36 | 0.5 | |
| Cladding/roof joint - uncaulked | | | | | |
| Front | 18m | 1.5 | 27 | 0.5 | |
| Rear | 18m | 1.5 | 27 | 0.5 | |
| Side (left) | 24m | 1.5 | 36 | 0.5 | |
| Side (right) | 24m | 1.5 | 36 | 0.5 | |
| Doors - closed | | | | | |
| Loading bay | $15.8m^2$ | 14 | 218 | 0.66 | |
| Front | 6.0m | 0.41 | 2.5 | 0.66 | |
| 2 x Rear | 12.0m | 0.41 | 4.9 | 0.66 | |
| Windows - closed | | | | | |
| 2 x Front | 6m | 0.23 | 1.4 | 0.66 | |
| Doors - open | | | | | |
| Loading bay | | | | | |
| 9 x horizontal strips, each | $1.75m^2$ | - | 1329 | 0.5 | |

### 5.2.4 Ventilation Strategy

The air leakage rate of a $300m^3$ single family dwelling is given as

(a) 3 ach at 50 Pa
(b) 10 ach at 50 Pa

In each case it is proposed to ventilate the dwelling at 0.5 ach using a balanced ventilation system with air-to-air heat recovery having a rated efficiency of 70%.

(i) Determine the overall ventilation efficiency for each level of airtightness, taking into account air infiltration.

(ii) Use the degree-day concept to estimate the annual energy saving using heat recovery for case (a) and (b) above compared with designing for an average natural ventilation rate of 0.7 ach assuming 4000 degree days.

Solution:

(i) Average infiltration rate for case (a) 3/20 = 0.15 ach
Average infiltration rate for case (b) 10/20 0.5 ach

Since no heat is recovered from infiltration/exfiltration losses, the overall heat recovery efficiency for case (a) becomes

$$\frac{70 \times 0.5}{0.5+0.15} = 54\%$$

and for case (b) becomes

$$\frac{70 \times 0.5}{0.5+0.5} = 35\%$$

(ii) Using equation 4.6 (Chapter 4), the annual energy requirements (without heat recovery) are

Case (a) $0.65 \times 300 \times \frac{4000}{3600} \times 0.1058$

$= 22.9$ GJ

Case (b) $= 35.3$ GJ

0.7 ach natural ventilation = 24.7 GJ

Taking into account heat recovery, actual ventilation heat loss becomes (equation 4.3, Chapter 4)

Case (a) (1 - 0.54) x 22.9 = 10.5 GJ

Case (b) (1 - 0.35) x 35.3 = 22.9 GJ

Case (c) 24.7 GJ

This example shows the importance of airtightness when installing air-to-air heat recovery.

## CHAPTER 6: Data Reference

# CHAPTER 6: Data Reference

## 6.1 CLIMATIC DATA

In calculating air infiltration rates, it is important to have information on the climate of the locality in which the building is situated. Weather recording stations are distributed countrywide and so it is usually possible to obtain climatic data derived from measurements in close proximity to the building site.

Table 6.1.1 shows the main source of meteorological data for each of the 12 countries participating in the Air Infiltration and Ventilation Centre. Also indicated in the Table are the numbers of principal meteorological stations.

Of the various climatic parameters, the ones that are of primary interest are wind speed and outdoor air temperature. While these two parameters may be considered independently, it is more often necessary to consider them together. This is because, for example, the windiest conditions rarely occur on the coldest days so that taking the extreme values of each parameter separately may result in an overestimate of infiltration. As indicated in Table 6.1.1 in some countries combined wind speed and temperature data are published, in others they are available on request (usually at some cost). An example of a wind speed vs temperature frequency table is shown in Table 6.1.2. This format is essential for air infiltration and ventilation design calculations.

As explained in Section 4.2, degree-days are of use in energy related evaluations as a measure of the severity of the climate. The basis of degree-days varies from country to country so care is required in using data from different sources. Table 6.1.1 gives the main sources of degree-day data, the value of the base temperature and some indication of the range of degree-days for each country. Further information should be obtained direct from the listed organisations.

## TABLE 6.1.1 Sources of climatic data

| Country | Meteorological Data: Main Source | Principal meteorological stations | Wind vs temperature frequency data available | Degree-day Data: Source | Base temperature °C | Range |
|---|---|---|---|---|---|---|
| Belgium | Institut Royal Meteorologique de Belgique<br>3 Avenue Circulaire<br>B-1180 Bruxelles<br>Belgium | 17 | Yes (on request) | As column 2 + monthly journal ETB-TUG | 15 | 2080-3100 |
| Canada | Atmospheric Environment Service<br>DOE<br>4905 Dufferin St<br>Downsview<br>Ontario, M3H 5T4<br>Canada | 340 | Yes | National Building Research Council of Canada<br>Building Research Note 138<br>1979 | 18 | 3200-12600 |
| Denmark | Det Danske Meteorologiske Institut<br>Lyngbyvej 100<br>DK 2100 Copenhagen<br>Denmark | 89 | Yes (on request) | Byggeteknik Technologisk Institut<br>Postbus 141<br>DK 2630 Tastrup<br>Denmark | 17 | 2460-3160 |
| Federal Republic of Germany | Deutscher Wetterdienst (Zentralamt)<br>Postfach 185<br>6050 Offenbach am Main<br>Frankfurter Strasse 135<br>Federal Republic of Germany | 53 | Yes | As column 2 published in Heizung-Lüftung Haustechnik | 20 | 3170-4590 |
| Finland | Finnish Meteorological Institute<br>PO Box 503<br>SF 00101 Helsinki 10<br>Finland | 32 | Yes | As column 2 | 17 | 3300-7500 |
| Netherlands | Koninklijk Nederlands Meteorologisch Institut<br>Wilhelminalaan 10<br>Postbus 201<br>3730 AE de Bilt<br>Netherlands | 16 | Yes | As column 2 | 18 | 2570-3820 |
| New Zealand | New Zealand Meteorological Service<br>PO Box 722<br>Wellington<br>New Zealand | 70 | Yes | As column 2 | 15 (or 18) | 300-1550 |
| Norway | Det Norske Meteorologiske Institutt<br>Nield Henr. Abels Vel 40<br>PO Box 320<br>Blindern<br>N-0314 Oslo 3<br>Norway | 52 | Yes | Norwegian Building Research Institute (Handbook 33) and "Norsk VVS" (monthly) | 17 | 4650-6400 |
| Sweden | Swedish Meteorological and Hydrological Institute<br>Folkborgsvägen 1<br>Box 923<br>S-60176 Norrköping<br>Sweden | 31 | Yes (on request) | As column 2 | 17 | 3010-5930 |
| Switzerland | l'Institute Suisse de Meteorologiqe<br>Krähbühlstrasse 58<br>CH 8044 Zurich<br>Switzerland | 63 | Yes | "Schweizer Inginieur und Architekt" and "Blätter für Heizung und Lüftung" | 20 | 2650-6400* |
| United Kingdom | Meteorological Office<br>London Road<br>Bracknell<br>Berkshire, RG12 2SZ<br>England | 52 | Yes (on request) | As column 2 + several monthly journals | 15.5 | 1840-2610 |
| United States of America | National Climatic Data Center<br>National Oceanic and Atmospheric Administration<br>Asheville<br>North Carolina 28801<br>USA | 277 | Yes | As column 2 | 18.3 | 630-9360 |

* *average for 80% populated area 3600*

## TABLE 6.1.2 Sample of wind speed vs temperature frequency table

KORRELATION LUFTTEMPERATUR (T) / WINDGESCHWINDIGKEIT (FF)

205 AACHEN 205 JAHR
GESAMTZAHL DER FAELLE ( MITTEL IN ZEHNTELN )
AUSGANGSWERTE = STUENDL. MESSUNGEN DES ZEITRAUMS 1951 - 65

| T/FF | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 12 | 14 | 16 | 18 | GE 20 M/SEC | SUMME | MITTEL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -17 | | | | | | | 1 | | | | | | | | | | 1 | 1 |
| -16 | 3 | 7 | 4 | 1 | 2 | 11 | 3 | | | | | | | | | | 31 | 21 |
| -15 | 2 | 6 | 6 | 6 | | 4 | 3 | | | | | | | | | | 27 | 18 |
| -14 | 5 | 14 | 6 | 9 | 11 | 13 | 2 | | | | | | | | | | 60 | 40 |
| -13 | 17 | 25 | 12 | 3 | 3 | 14 | 6 | 3 | | | | | | | | | 83 | 55 |
| -12 | 20 | 27 | 12 | 6 | 5 | 9 | 7 | 5 | | | | | | | | | 91 | 61 |
| -11 | 19 | 36 | 34 | 21 | 4 | 9 | 10 | 9 | | | | | | | | | 142 | 95 |
| -10 | 20 | 50 | 48 | 29 | 7 | 14 | 9 | 6 | 1 | | | | | | | | 184 | 123 |
| -9 | 43 | 72 | 50 | 36 | 13 | 10 | 5 | 7 | 5 | 1 | | | | | | | 242 | 161 |
| -8 | 35 | 87 | 82 | 59 | 14 | 16 | 7 | 4 | | | | | | | | | 304 | 203 |
| -7 | 54 | 89 | 85 | 73 | 20 | 11 | 6 | 4 | 4 | | | | | | | | 346 | 231 |
| -6 | 66 | 99 | 96 | 94 | 46 | 22 | 4 | 3 | 2 | | | | | | | | 432 | 288 |
| -5 | 143 | 165 | 123 | 94 | 42 | 27 | 11 | 2 | 3 | | | | | | | | 610 | 407 |
| -4 | 150 | 255 | 207 | 156 | 104 | 54 | 22 | 8 | 4 | 5 | 1 | | | | | | 966 | 644 |
| -3 | 218 | 357 | 315 | 194 | 130 | 87 | 42 | 18 | 7 | 1 | 2 | | | | | | 1371 | 914 |
| -2 | 289 | 508 | 463 | 359 | 190 | 107 | 70 | 34 | 5 | 2 | 2 | 3 | | | | | 2032 | 1355 |
| -1 | 324 | 596 | 566 | 457 | 272 | 153 | 82 | 30 | 8 | 6 | 6 | 9 | 1 | | | | 2510 | 1673 |
| -0 | 340 | 576 | 484 | 538 | 308 | 196 | 75 | 39 | 35 | 23 | 18 | 5 | | | | | 2657 | 1771 |
| 0 | 451 | 985 | 838 | 671 | 554 | 319 | 125 | 71 | 43 | 22 | 21 | 8 | | | | | 4068 | 2712 |
| 1 | 361 | 945 | 865 | 762 | 548 | 334 | 162 | 109 | 62 | 54 | 39 | 9 | 5 | | | | 4275 | 2850 |
| 2 | 399 | 968 | 939 | 843 | 588 | 391 | 245 | 155 | 98 | 76 | 57 | 24 | 4 | | | | 4792 | 3195 |
| 3 | 381 | 896 | 968 | 903 | 715 | 468 | 336 | 235 | 130 | 81 | 101 | 20 | 1 | | | | 5235 | 3490 |
| 4 | 412 | 980 | 1002 | 902 | 662 | 469 | 345 | 273 | 208 | 123 | 146 | 34 | 4 | 1 | | | 5561 | 3707 |
| 5 | 429 | 1026 | 1056 | 963 | 722 | 490 | 433 | 300 | 275 | 177 | 165 | 41 | 6 | | | | 6083 | 4055 |
| 6 | 439 | 1060 | 1075 | 970 | 672 | 465 | 399 | 330 | 221 | 152 | 160 | 58 | 7 | | | | 6008 | 4005 |
| 7 | 495 | 1059 | 1064 | 892 | 668 | 548 | 432 | 349 | 222 | 161 | 190 | 62 | 17 | 4 | | | 6153 | 4102 |
| 8 | 441 | 1134 | 1206 | 1017 | 763 | 541 | 468 | 371 | 237 | 152 | 196 | 72 | 6 | | | | 6714 | 4476 |
| 9 | 423 | 1228 | 1160 | 991 | 725 | 596 | 453 | 351 | 216 | 154 | 145 | 47 | 3 | | | | 6492 | 4328 |
| 10 | 465 | 1426 | 1298 | 998 | 746 | 598 | 377 | 275 | 172 | 165 | 126 | 25 | 4 | 4 | | | 6679 | 4453 |
| 11 | 475 | 1355 | 1255 | 1151 | 788 | 590 | 380 | 256 | 166 | 98 | 135 | 16 | 3 | 1 | | | 6669 | 4446 |
| 12 | 574 | 1413 | 1346 | 1167 | 806 | 586 | 388 | 234 | 156 | 99 | 94 | 18 | 5 | | | | 6884 | 4589 |
| 13 | 527 | 1533 | 1372 | 1178 | 799 | 603 | 358 | 253 | 156 | 95 | 73 | 18 | | | | | 6965 | 4643 |
| 14 | 479 | 1470 | 1336 | 1030 | 740 | 589 | 346 | 216 | 101 | 60 | 48 | 5 | | | | | 6420 | 4280 |
| 15 | 360 | 1281 | 1277 | 897 | 690 | 516 | 297 | 188 | 119 | 50 | 24 | 5 | | | | | 5704 | 3803 |
| 16 | 347 | 1116 | 1112 | 811 | 623 | 454 | 248 | 169 | 81 | 35 | 29 | 3 | | | | | 5028 | 3352 |
| 17 | 256 | 999 | 974 | 687 | 546 | 361 | 228 | 123 | 73 | 40 | 26 | 4 | | | | | 4347 | 2898 |
| 18 | 219 | 790 | 836 | 592 | 440 | 287 | 175 | 58 | 48 | 16 | 14 | 4 | | | | | 3509 | 2339 |
| 19 | 138 | 643 | 673 | 493 | 350 | 242 | 125 | 57 | 33 | 13 | 7 | | | | | | 2776 | 1851 |
| 20 | 121 | 471 | 574 | 355 | 266 | 178 | 101 | 57 | 23 | 12 | 2 | | | | | | 2160 | 1440 |
| 21 | 55 | 379 | 449 | 308 | 171 | 131 | 61 | 25 | 16 | 6 | 1 | | | | | | 1613 | 1075 |
| 22 | 42 | 273 | 336 | 246 | 125 | 92 | 52 | 17 | 10 | 2 | 4 | | | | | | 1179 | 786 |
| 23 | 34 | 240 | 288 | 199 | 90 | 33 | 20 | 5 | 5 | 6 | 5 | | | | | | 925 | 617 |
| 24 | 12 | 177 | 241 | 167 | 75 | 37 | 18 | 7 | 2 | 3 | 3 | | | | | | 742 | 495 |
| 25 | 9 | 142 | 166 | 135 | 57 | 26 | 2 | 8 | 5 | 2 | | | | | | | 552 | 368 |
| 26 | 7 | 102 | 141 | 84 | 47 | 24 | 11 | 5 | 1 | | | | | | | | 422 | 281 |
| 27 | 6 | 56 | 85 | 56 | 34 | 16 | 9 | 2 | 3 | 1 | | | | | | | 268 | 179 |
| 28 | 8 | 42 | 68 | 42 | 9 | 8 | 7 | 2 | 3 | | | | | | | | 189 | 126 |
| 29 | 1 | 33 | 45 | 24 | 11 | 1 | 6 | 2 | 1 | | | | | | | | 124 | 83 |
| 30 | | 21 | 34 | 19 | 7 | 4 | 1 | | | | | | | | | | 86 | 57 |
| 31 | 3 | 12 | 17 | 7 | 4 | 7 | 3 | 3 | | | | | | | | | 56 | 37 |
| 32 | 1 | 5 | 11 | 3 | 3 | 3 | 2 | | 1 | | | | | | | | 29 | 19 |
| 33 | | 2 | 1 | 9 | 5 | 1 | 1 | | | | | | | | | | 19 | 13 |
| 34 | | 1 | 1 | 3 | 2 | | | | | | | | | | | | 7 | 5 |
| SUM | 10159 | 27252 | 26702 | 21715 | 15202 | 10865 | 6959 | 4708 | 2961 | 1905 | 1830 | 490 | 64 | 10 | | | 130822 | 87215 |
| MTL | 6773 | 18168 | 17801 | 14477 | 10135 | 7243 | 4639 | 3139 | 1974 | 1270 | 1220 | 327 | 43 | 7 | | | 87215 | |

## 6.2 WIND PRESSURE DATA

The data presented in this section are based on the interpolation of published material, much of which was presented at the AIVC's Wind Pressure Workshop[1]. The values presented must only be regarded as approximate and therefore, if more accurate design data are required, recourse to specific wind tunnel or full scale measurements will have to be considered. The intention of these data sets is to provide the user with an indication of the range of pressure coefficient values which might be anticipated for various building orientations and for various degrees of shielding. The data presented is as follows:

Tables 6.2.1 to 6.2.6 cover low-rise buildings of typically no more than 3 storeys. Three degrees of shielding are considered; these are

1. open countryside - no obstructions - exposed.

2. rural surroundings - some obstructions - semi sheltered.

3. urban - building surrounded on all sides by obstructions of similar size - sheltered.

For each condition, the pressure coefficient is expressed as a single average value for each face of the building, where the reference pressure height for wind speed is taken as the building height.

Data are presented for each face and for the roof surface, where roof pitch angles of

1. $<10^{\circ}$
2. $11-30^{\circ}$
3. $> 30^{\circ}$

are considered.

Tables 6.2.1 to 6.2.3 cover data for buildings of length to width ratios of 1:1 and Tables 6.2.4 to 6.2.6 cover data for length to width ratios of 2:1.

Data depicted in Figure 6.2.1 contain results by Bowen[2] showing the vertical dependency of pressure coefficient for tall buildings.

Pressure coefficient data depicted in Figure 6.2.2[3] apply to flue openings situated above roof level. They are for sheltered conditions with a reference wind speed taken at roof height.

Figure 6.2.3 presents a graphical method for the siting of flue openings to prevent backdraughting[4].

Table 6.2.7 contains recommended terrain coefficients for converting wind speed measured at an open site, at a level of 10m, to roof height values[5,6].

Tables 6.2.8 and 6.2.9 contain terrain and shielding coefficients for use in the LBL model (Section 5.2.1)[6].

In addition to the results of Bowen[3], other important sources of wind pressure coefficient data for air infiltration calculations include BS5295[5] and Wiren[7].

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

REFERENCES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AIC-TN-13.1-84, Brussels, Belgium, March 1984.

2 Bowen, J J
A wind tunnel investigation using simple building models to obtain mean surface wind pressure coefficients for air infiltration estimates.
NRC Report LTR-LA-209, National Research Council, Canada, 1976.

3 Lugtenburg, A
Air flow around buildings - pressure measurements on flue outlets. (Luchtbewegning om gebouwen - Drukmetingen aan afvoerkanalen).
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4 Ventilatie van woongebouwen (Ventilation in dwellings)
NPR 1088 Nov 1975
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5 BS5925
Code of Practice for the design of buildings; ventilation principles and designing for natural ventilation.
British Standards Institution, 1980.

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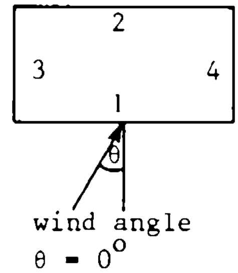
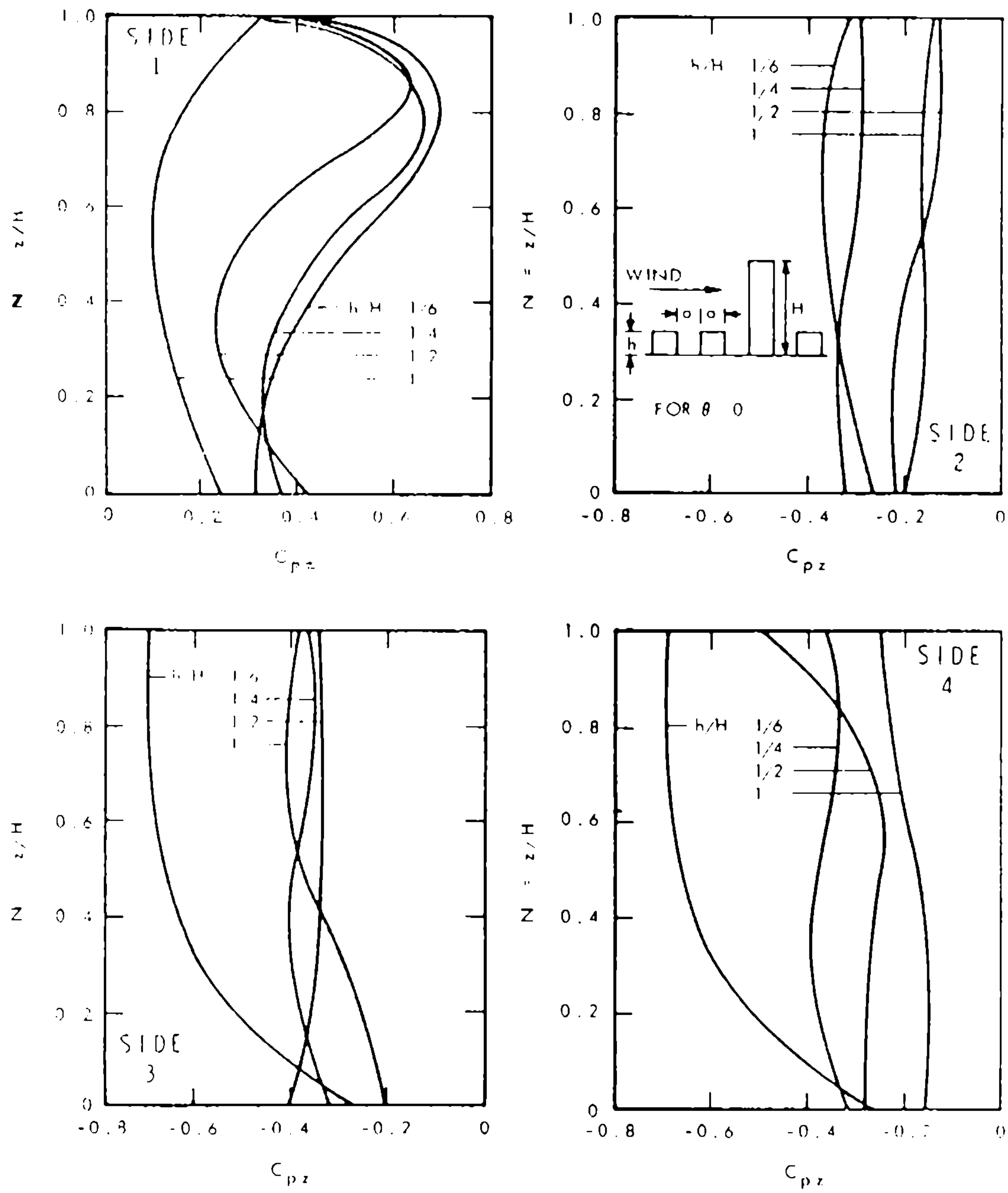
Measurement of infiltrartion using fan pressurization and weather data.
1st AIC Conference 'Air Infiltration Instrumentation and Measurement Techniques', Proceedings, 1980, UK.

7 Wiren, B G
Effects of surrounding buildings on wind pressure distributions and ventilation losses for single-family houses. Part 1: 1½-storey detached houses.
Bulletin M85:19, National Swedish Institute for Building Research, Gavle, Sweden, 1985.

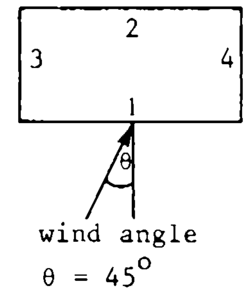
Figure 6.2.1 Vertical distribution of mean wind pressure coefficients for various surrounding obstruction heights.

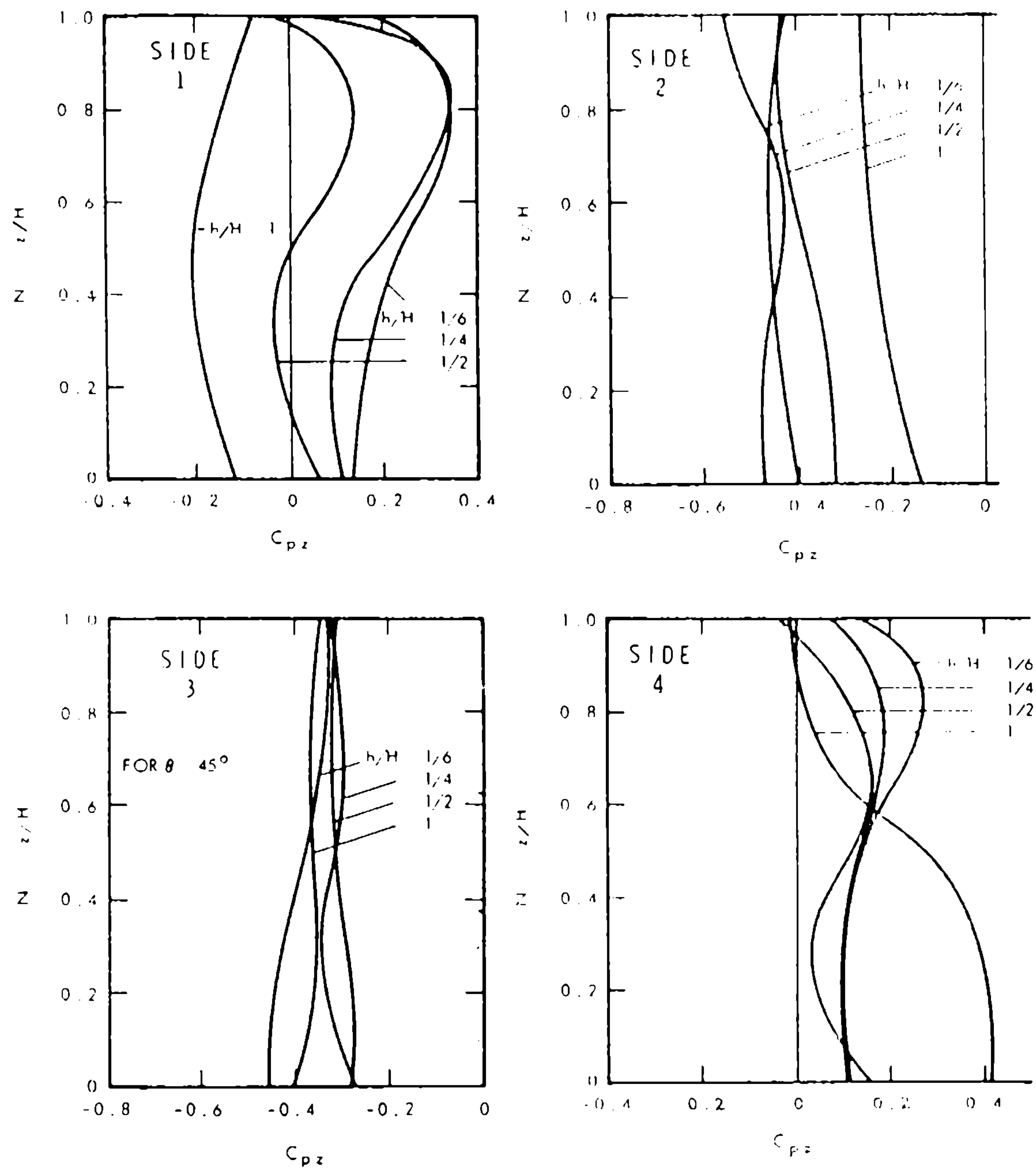



*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

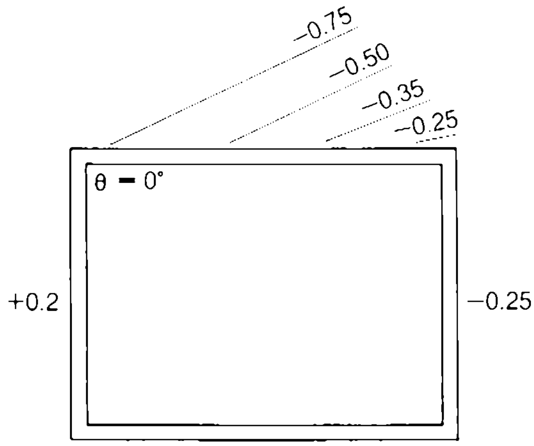
Figure 6.2.1 (continued)



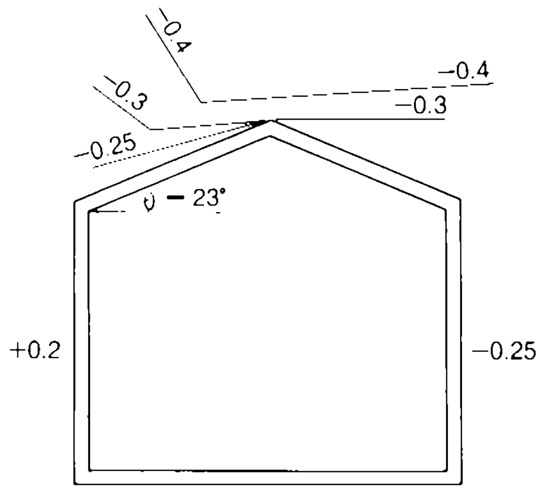




*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

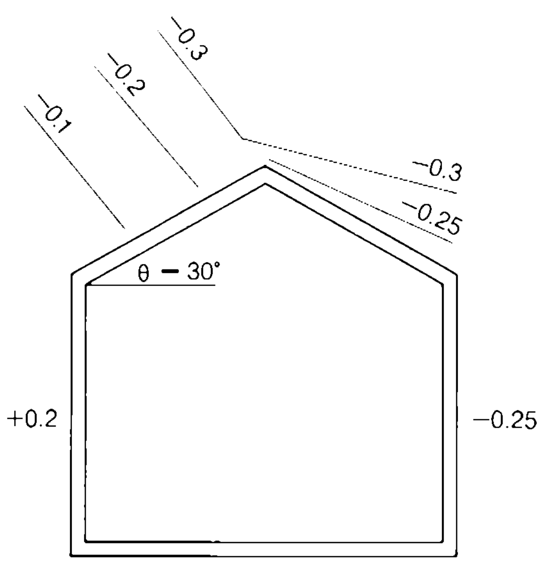
Figure 6.2.2 Wind pressure coefficients for protrusions above roof level (see Reference 3)




(a) Roof pitch, θ, = $0^{o}$



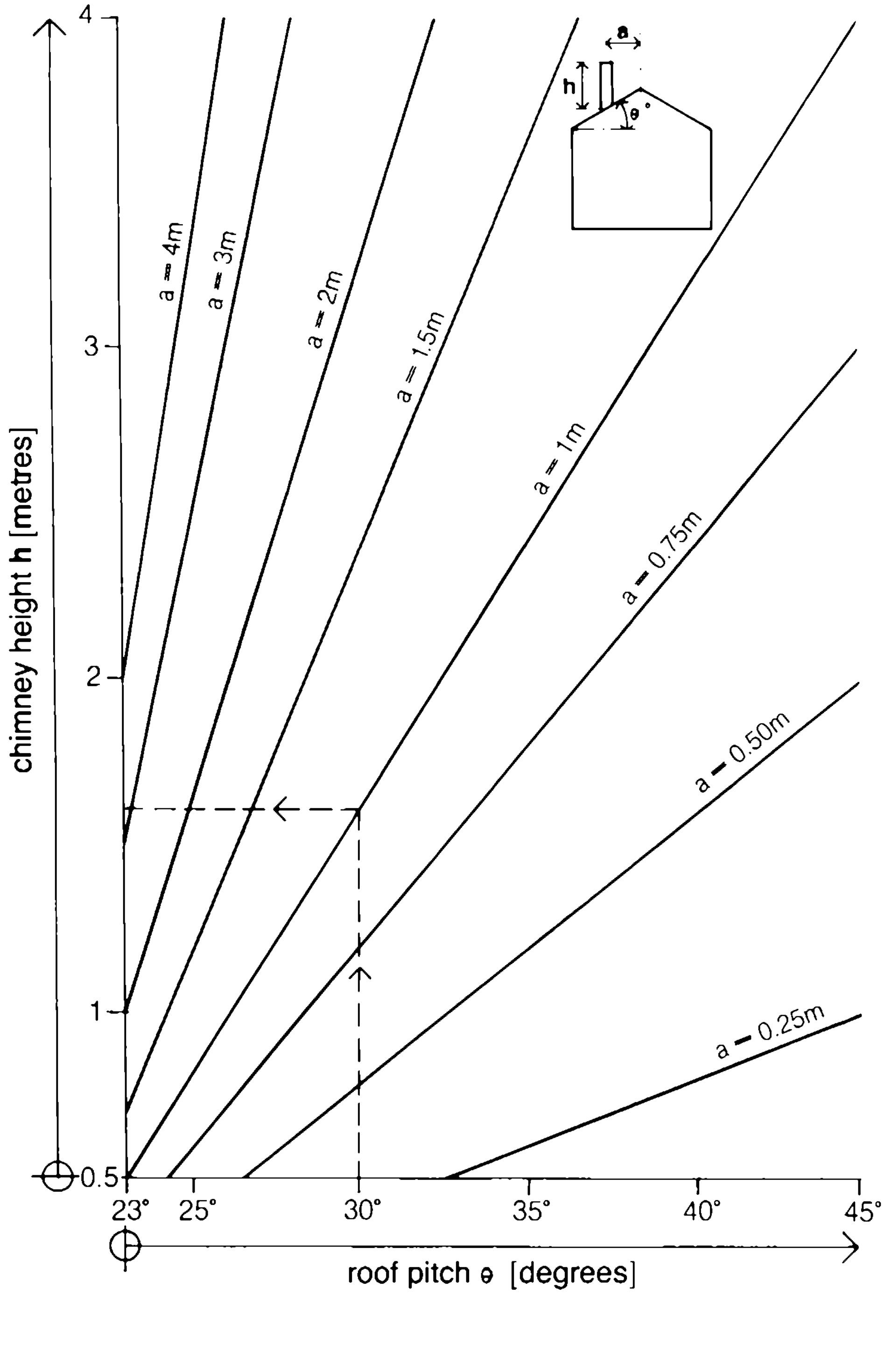

(b) Roof pitch, θ, = $23^{o}$




(c) Roof pitch, θ, = $30^{o}$

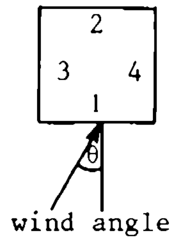
*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

Figure 6.2.3 Flue height, h, to avoid back draughting (see Reference 3)




*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

TABLE 6.2.1 Wind Pressure Coefficient Data




Low-rise buildings (up to 3 storeys)

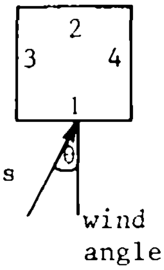
Length to width ratio 1:1
Shielding condition Exposed
Wind speed reference level = building height

Wind Angle

| Location | | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
|---|---|---|---|---|---|---|---|---|---|
| Face 1 | | .7 | .35 | -.5 | -.4 | -.2 | -.4 | -.5 | .35 |
| Face 2 | | -.2 | -.4 | -.5 | .35 | .7 | .35 | -.5 | -.4 |
| Face 3 | | -.5 | .35 | .7 | .35 | -.5 | -.4 | -.2 | -.4 |
| Face 4 | | -.5 | -.4 | -.2 | -.4 | -.5 | .35 | .7 | .35 |
| | | | | | | | | | |
| "Weighted" mean | | -.05 | -.03 | -.05 | -.03 | -.05 | -.03 | -.05 | -.03 |
| | | | | | | | | | |
| Roof (<10° pitch) | Front | -.8 | -.7 | -.6 | -.5 | -.4 | -.5 | -.6 | -.7 |
| | Rear | -.4 | -.5 | -.6 | -.7 | -.8 | -.7 | -.6 | -.5 |
| Average | | -.6 | -.6 | -.6 | -.6 | -.6 | -.6 | -.6 | -.6 |
| | | | | | | | | | |
| Roof (11-30° pitch) | Front | -.4 | -.5 | -.6 | -.5 | -.4 | -.5 | -.6 | -.5 |
| | Rear | -.4 | -.5 | -.6 | -.5 | -.4 | -.5 | -.6 | -.5 |
| Average | | -.4 | -.5 | -.6 | -.5 | -.4 | -.5 | -.6 | -.5 |
| | | | | | | | | | |
| Roof (>30° pitch) | Front | .3 | -.4 | -.6 | -.4 | -.5 | -.4 | -.6 | -.4 |
| | Rear | -.5 | -.4 | -.6 | -.4 | .3 | -.4 | -.6 | -.4 |
| Average | | -.1 | -.4 | -.6 | -.4 | -.1 | -.4 | -.6 | -.4 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

TABLE 6.2.2 Wind Pressure Coefficient Data




Low-rise buildings (up to 3 storeys)

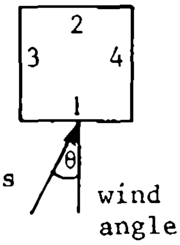
Length to width ratio: 1:1
Shielding condition: Surrounded by obstructions equivalent to half the height of the building.
Wind speed reference level = building height

Wind Angle

| Location | | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
|---|---|---|---|---|---|---|---|---|---|
| Face 1 | | .4 | .1 | -.3 | -.35 | -.2 | -.35 | -.3 | -.1 |
| Face 2 | | -.2 | -.35 | -.3 | .1 | .4 | .1 | -.3 | -.35 |
| Face 3 | | -.3 | .1 | .4 | .1 | -.3 | -.35 | -.2 | -.35 |
| Face 4 | | -.3 | -.35 | -.2 | -.35 | -.3 | .1 | .4 | .1 |
| | | | | | | | | | |
| "Weighted" mean | | -.1 | -.13 | -.1 | -.13 | -.1 | -.13 | -.1 | -.13 |
| | | | | | | | | | |
| Roof (<10° pitch) | Front | -.6 | -.5 | -.4 | -.5 | -.6 | -.5 | -.4 | -.5 |
| | Rear | -.6 | -.5 | -.4 | -.5 | -.6 | -.5 | -.4 | -.5 |
| Average | | -.6 | -.5 | -.4 | -.5 | -.6 | -.5 | -.4 | -.5 |
| | | | | | | | | | |
| Roof (11-30° pitch) | Front | -.35 | -.45 | -.55 | -.45 | -.35 | -.45 | -.55 | -.45 |
| | Rear | -.35 | -.45 | -.55 | -.45 | -.35 | -.45 | -.55 | -.45 |
| Average | | -.35 | -.45 | -.55 | -.45 | -.35 | -.45 | -.55 | -.45 |
| | | | | | | | | | |
| Roof (>30° pitch) | Front | .3 | -.5 | -.6 | -.5 | -.5 | -.5 | -.6 | -.5 |
| | Rear | -.5 | -.5 | -.6 | -.5 | .3 | -.5 | -.6 | -.5 |
| Average | | -.1 | -.5 | -.6 | -.5 | -.1 | -.5 | -.6 | -.5 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

## TABLE 6.2.3 Wind Pressure Coefficient Data




Low rise buildings (up to 3 storeys)

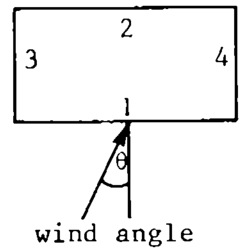
Length to width ratio — 1:1
Shielding condition — Surrounded by obstructions equal to height of the building.
Wind speed reference level = building height

Wind Angle

| Location | | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
|---|---|---|---|---|---|---|---|---|---|
| Face 1 | | .2 | .05 | -.25 | -.3 | -.25 | -.3 | -.25 | .05 |
| Face 2 | | -.25 | -.3 | -.25 | .05 | .2 | .05 | -.25 | -.3 |
| Face 3 | | -.25 | .05 | .2 | .05 | -.25 | -.3 | -.25 | -.3 |
| Face 4 | | -.25 | -.3 | -.25 | -.3 | -.25 | .05 | .2 | .05 |
| | | | | | | | | | |
| "Weighted" mean | | -.15 | -.15 | -.15 | -.15 | -.15 | -.15 | -.15 | -.15 |
| | | | | | | | | | |
| Roof (<10° pitch) | Front | -.5 | -.5 | -.4 | -.5 | -.5 | -.5 | -.4 | -.5 |
| | Rear | -.5 | -.5 | -.4 | -.5 | -.5 | -.5 | -.4 | -.5 |
| Average | | -.5 | -.5 | -.4 | -.5 | -.5 | -.5 | -.4 | -.5 |
| | | | | | | | | | |
| Roof (11-30° pitch) | Front | -.3 | -.4 | -.5 | -.4 | -.3 | -.4 | -.5 | -.4 |
| | Rear | -.3 | -.4 | -.5 | -.4 | -.3 | -.4 | -.5 | -.4 |
| Average | | -.3 | -.4 | -.5 | -.4 | -.3 | -.4 | -.5 | -.4 |
| | | | | | | | | | |
| Roof (>30° pitch) | Front | .25 | -.3 | -.5 | -.3 | -.4 | -.3 | -.5 | -.3 |
| | Rear | -.4 | -.3 | -.5 | -.3 | .25 | -.3 | -.5 | -.3 |
| Average | | -.08 | -.3 | -.5 | -.3 | -.08 | -.3 | -.5 | -.3 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## TABLE 6.2.4 Wind Pressure Coefficient Data




Low-rise buildings (up to 3 storeys)

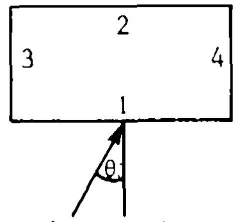
Length to width ratio 2:1
Shielding condition Exposed
Wind speed reference level - building height

Wind Angle

| Location | | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
|---|---|---|---|---|---|---|---|---|---|
| Face 1 | | 0.5 | 0.25 | -0.5 | -0.8 | -0.7 | -0.8 | -0.5 | 0.25 |
| Face 2 | | -0.7 | -0.8 | -0.5 | 0.25 | 0.5 | 0.25 | -0.5 | -0.8 |
| Face 3 | | -0.9 | 0.2 | 0.6 | 0.2 | -0.9 | -0.6 | -0.35 | -0.6 |
| Face 4 | | -0.9 | -0.6 | -0.35 | -0.6 | -0.9 | 0.2 | 0.6 | 0.2 |
| | | | | | | | | | |
| "Weighted" mean | | -0.48 | -0.17 | -0.06 | -0.17 | -0.48 | -0.17 | -0.06 | -0.17 |
| | | | | | | | | | |
| Roof (<10° pitch) | Front | -0.7 | -0.7 | -0.8 | -0.7 | -0.7 | -0.7 | -0.8 | -0.7 |
| | Rear | -0.7 | -0.7 | -0.8 | -0.7 | -0.7 | -0.7 | -0.8 | -0.7 |
| Average | | -0.7 | -0.7 | -0.8 | -0.7 | -0.7 | -0.7 | -0.8 | -0.7 |
| | | | | | | | | | |
| Roof (11-30° pitch) | Front | -0.7 | -0.7 | -0.7 | -0.6 | -0.5 | -0.6 | -0.7 | -0.7 |
| | Rear | -0.5 | -0.6 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.6 |
| Average | | -0.6 | -0.65 | -0.7 | -0.65 | -0.6 | -0.65 | -0.7 | -0.65 |
| | | | | | | | | | |
| Roof (>30° pitch) | Front | 0.25 | 0 | -0.6 | -0.9 | -0.8 | -0.9 | -0.6 | 0 |
| | Rear | -0.8 | -0.9 | -0.6 | 0 | 0.25 | 0 | -0.6 | -0.9 |
| Average | | -0.18 | -0.45 | -0.6 | -0.45 | -0.18 | -0.45 | -0.6 | -0.45 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

TABLE 6.2.5 Wind Pressure Coefficient Data



wind angle

Low-rise buildings (up to 3 storeys)

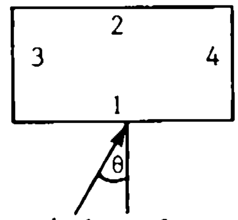
Length to width ratio 2:1
Shielding condition Semi sheltered
Wind speed reference level = building height

Wind Angle

| Location | | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
|---|---|---|---|---|---|---|---|---|---|
| Face 1 | | 0.5 | 0.25 | -0.5 | -0.8 | -0.7 | -0.8 | -0.5 | 0.25 |
| Face 2 | | -0.7 | -0.8 | -0.5 | 0.25 | 0.5 | 0.25 | -0.5 | -0.8 |
| Face 3 | | -0.9 | 0.2 | 0.6 | 0.2 | -0.9 | -0.6 | -0.35 | -0.6 |
| Face 4 | | -0.9 | -0.6 | -0.35 | -0.6 | -0.9 | 0.2 | 0.6 | 0.2 |
| | | | | | | | | | |
| "Weighted" mean | | -0.48 | -0.17 | -0.06 | -0.17 | -0.48 | -0.17 | -0.06 | -0.17 |
| | | | | | | | | | |
| Roof (<10° pitch) | Front | -0.7 | -0.7 | -0.8 | -0.7 | -0.7 | -0.7 | -0.8 | -0.7 |
| | Rear | -0.7 | -0.7 | -0.8 | -0.7 | -0.7 | -0.7 | -0.8 | -0.7 |
| Average | | -0.7 | -0.7 | -0.8 | -0.7 | -0.7 | -0.7 | -0.8 | -0.7 |
| | | | | | | | | | |
| Roof (11-30° pitch) | Front | -0.7 | -0.7 | -0.7 | -0.6 | -0.5 | -0.6 | -0.7 | -0.7 |
| | Rear | -0.5 | -0.6 | -0.7 | -0.7 | -0.7 | -0.7 | -0.7 | -0.6 |
| Average | | -0.6 | -0.65 | -0.7 | -0.65 | -0.6 | -0.65 | -0.7 | -0.65 |
| | | | | | | | | | |
| Roof (>30° pitch) | Front | 0.25 | 0 | -0.6 | -0.9 | -0.8 | -0.9 | -0.6 | 0 |
| | Rear | -0.8 | -0.9 | -0.6 | 0 | 0.25 | 0 | -0.6 | -0.9 |
| Average | | -0.18 | -0.45 | -0.6 | -0.45 | -0.18 | -0.45 | -0.6 | -0.45 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

TABLE 6.2.6 Wind Pressure Coefficient Data



wind angle

Low-rise buildings (up to 3 storeys)

Length to width ratio 2:1
Shielding condition Sheltered
Wind speed reference level = building height

Wind Angle

| Location | | 0 | 45 | 90 | 135 | 180 | 225 | 270 | 315 |
|---|---|---|---|---|---|---|---|---|---|
| Face 1 | | 0.06 | -0.12 | -0.2 | -0.38 | -0.3 | -0.38 | -0.2 | -0.12 |
| Face 2 | | -0.3 | -0.38 | -0.2 | -0.12 | 0.06 | -0.12 | -0.2 | -0.38 |
| Face 3 | | -0.3 | 0.15 | 0.18 | 0.15 | -0.3 | -0.32 | -0.2 | -0.32 |
| Face 4 | | -0.3 | -0.32 | -0.2 | -0.32 | -0.3 | 0.15 | 0.18 | 0.15 |
| | | | | | | | | | |
| "Weighted" mean | | -0.24 | -0.14 | -0.07 | -0.14 | -0.24 | -0.14 | -0.07 | -0.14 |
| | | | | | | | | | |
| Roof (<10° pitch) | Front | -0.49 | -0.46 | -0.41 | -0.46 | -0.49 | -0.46 | -0.41 | -0.46 |
| | Rear | -0.49 | -0.46 | -0.41 | -0.46 | -0.49 | -0.46 | -0.41 | -0.46 |
| Average | | -0.49 | -0.46 | -0.41 | -0.46 | -0.49 | -0.46 | -0.41 | -0.46 |
| | | | | | | | | | |
| Roof (11-30° pitch) | Front | -0.49 | -0.46 | -0.41 | -0.46 | -0.4 | -0.46 | -0.41 | -0.46 |
| | Rear | -0.4 | -0.46 | -0.41 | -0.46 | -0.49 | -0.46 | -0.41 | -0.46 |
| Average | | -0.45 | -0.46 | -0.41 | -0.46 | -0.45 | -0.46 | -0.41 | -0.46 |
| | | | | | | | | | |
| Roof (>30° pitch) | Front | 0.06 | -0.15 | -0.23 | -0.6 | -0.42 | -0.6 | -0.23 | -0.15 |
| | Rear | -0.42 | -0.6 | -0.23 | -0.15 | -0.06 | -0.15 | -0.23 | -0.6 |
| Average | | -0.18 | -0.4 | -0.23 | -0.4 | -0.18 | -0.4 | -0.23 | -0.4 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

TABLE 6.2.7 Terrain coefficients for wind profile equations (BS5925)

$$\frac{U}{U_m} = K z^a$$

where $U_m$ = windspeed measured in open countryside at a standard height of 10m.

$U$ = windspeed at a height, z, above ground.

K,a = constants dependent on terrain (see below)

| Terrain coefficients | K | a |
|---|---|---|
| Open flat country | 0.68 | 0.17 |
| Country with scattered wind breaks | 0.52 | 0.20 |
| Urban | 0.35 | 0.25 |
| City | 0.21 | 0.33 |

TABLE 6.2.8 Terrain coefficients for LBL model (see Section 5.1.1)

$$\frac{U}{U'} = \frac{\alpha\,(z/10)^{\gamma}}{\alpha'(z'/10)^{\gamma'}}$$

where U = required site wind speed at level z above ground.

U' = measured windspeed at level z' above ground (see below).

$\alpha', \gamma'$ = constants dependent on offsite terrain conditions.

$\alpha, \gamma$ = constants dependent on onsite terrain conditions (see below).

| Terrain description | $\gamma$ | $\alpha$ |
|---|---|---|
| Ocean or other body of water with at least 5km of unrestricted expanse | 0.10 | 1.30 |
| Flat terrain with some isolated obstacles, e.g. buildings of trees well separated from each other | 0.15 | 1.00 |
| Rural areas with low buildings, trees, etc. | 0.20 | 0.85 |
| Urban, industrial or forest areas. | 0.25 | 0.67 |
| Centre of large city, e.g. Manhattan | 0.35 | 0.47 |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

TABLE 6.2.9 Generalised shielding coefficients for LBL model (see Section 5.1.1)

| Shielding Class | C′ | Description |
|---|---|---|
| I | 0.34 | No obstructions or local shielding whatsoever |
| II | 0.30 | Light local shielding with few obstructions |
| III | 0.25 | Moderate local shielding, some obstructions within two house heights |
| IV | 0.19 | Heavy shielding, obstructions around most of perimeter |
| V | 0.11 | Very heavy shielding, large obstruction surrounding perimeter within two house heights |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## 6.3 AIR LEAKAGE DATA

This section of the Guide is devoted to the presentation of available leakage data in a format that will enable the designer to select appropriate values for inclusion in air infiltration models. The data is presented in tabular form, principally in terms of leakage characteristics (flow coefficients and exponent values). This represents the most general description of flow performance from which other formats such as equivalent leakage area (ELA) may be derived. Since there is yet no universally accepted definition of ELA, it is thought that the presentation of data in this form should be restricted to country-specific supplements.

The information reproduced in this section is based on a survey of data published in the literature and, as with the wind pressure coefficient data, provides only a very approximate guide. Furthermore, there are, as yet, no suitable values for many component categories. Where there was sufficient information, mean values, the range of data and standard deviations are given.

Since the source data came from many countries and were published in many different formats, the harmonising of material proved difficult. Essentially the source data could be classified in the following categories:

<u>Case A</u>
Tabulated test values of pressure differences with corresponding leakage rates.

<u>Case B</u>
Similar data in the form of a graph.

<u>Case C</u>
As 'B' but plotted on logarithmic scales with a 'best fit' straight line. This assumes a relationship of the form:

$$Ln = n\, Ln\Delta p + Ln\, K$$

where $Q$ = leakage flow rate
$K$ = flow coefficient
$\Delta p$ = pressure difference
$n$ = flow exponent

<u>Case D</u>
Tabulated values of K and n for various conditions.

<u>Case E</u>
A single point value of leakage rate at a reference pressure difference.

Case F
Values of Equivalent Orifice Area (A) in the relationship:

$$Q = 4000\ Cd\ A\ (\Delta p)^{1/2} \qquad \text{(Imperial Units)}$$

The values of A being quoted for a reference pressure difference - generally 0.3 in $H_2O$.

Case G
Values of Effective Leakage Area ($A_{eff}$) in the relationship:

$$Q = A_{eff}\ \left(\frac{2\Delta p}{\rho}\right)$$

The values of $A_{eff}$ being quoted for a reference pressure difference - generally 4 Pa.

The flow rate Q could be quoted per unit length of crack, per unit area of opening or per unit volume of building enclosure. For the purpose of this analysis it was decided to attempt to relate all data to an exponential law:

$$Q = K\ (\Delta p)^n$$

All quantities to be expressed in SI units.

A number of assumptions concerning the above Cases have had to be made as explained below:

Case A - A logarithmic regression line was computed and the coefficient K and the exponent n determined.

Case B - Points were taken from the best fit line and treated as in Case A.

Case C - Value of K and n read from graph.

Case D - Data in immediately usable form.

Case E - A value of n was assumed and the value of K determined. (Note: K = value of Q for $\Delta p$ = 1 Pa)

The value of n chosen:

| Type of opening | n |
|---|---|
| Large openings | 0.5 |
| Cracks (doors and windows) | 0.66 |
| Porous materials with joints | 0.75 |
| Porous materials alone | 1.0 |

Case F - Given A and the reference pressure difference and assuming a coefficient of discharge of 0.6, a corresponding value of Q was calculated. This was then extrapolated to $\Delta p = 1$ to determine K using the relationship $Q = K(\Delta p)^n$ and a value of n as above.

The relationship for equivalent orifice area assumes a flow exponent of 0.5. Had this been used, different values of K would have been obtained. However, it is known that for many openings, say doors and windows, the flow exponent is larger than 0.5.

Case G - The procedure was similar to Case F. Assumptions were similar with the addition of air density 1.2 $kg/m^3$.

It is to be noted that although a single value of leakage rate (quoted at a reference pressure difference) may have been the mean of many tests, the extrapolation from it to a reference pressure difference of 1 Pa using a standard value exponent could result in a value for K very different from that suggested by the actual experimental results.

TABLE 6.3.2 Continued

(Data expressed for each metre length of joint)

| Item | Flow Coefficient ($dm^3/s.m.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev | mean | max. | min. | s. dev |
| Horizontal sliding - double | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Timber | 0.06 | | | 0.04 | 0.66 | | | |
| Timber clad | | | | | | | | |
| Metal | 0.08 | 0.13 | 0.04 | 0.03 | 0.66 | | | |
| Plastic | 0.08 | | | | 0.66 | | | |
| Unweatherstripped: | | | | | | | | |
| Timber | 0.19 | 0.31 | 0.08 | 0.07 | 0.66 | | | |
| Timber clad | | | | | | | | |
| Metal | 0.22 | 0.43 | 0.12 | 0.1 | 0.63 | 0.67 | 0.55 | 0.04 |
| Vertical sliding - single | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Timber | | | | | | | | |
| Timber clad | | | | | | | | |
| Metal | 0.09 | | | 0.03 | 0.66 | | | |
| Plastic | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Timber | 0.16 | | | | 0.66 | | | |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| Vertical sliding - double | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Timber | 0.07 | | | 0.04 | 0.66 | | | |
| Timber clad | 0.07 | | | 0.04 | 0.66 | | | |
| Metal | 0.18 | 0.28 | 0.04 | 0.08 | 0.66 | 0.79 | 0.56 | |
| Plastic | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Timber | 0.17 | | | | 0.66 | | | |
| Timber clad | | | | | | | | |
| Metal | 0.45 | 1.2 | 0.2 | 0.35 | 0.58 | 0.69 | 0.45 | 0.07 |
| Plastic | | | | | | | | |
| Skylight | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Timber | | | | | | | | |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Timber | | | | | | | | |
| Timber clad | | | | | | | | |
| Metal | 0.18 | 3.07 | 0.16 | 0.73 | 0.55 | 0.59 | 0.50 | 0.04 |
| Plastic | | | | | | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## TABLE 6.3.3 AIR LEAKAGE DATA - Wall/Window Frames and Door Frames

**(Data expressed for each metre length of joint)**

| Item Wall Material | Frame Material | Flow Coefficient ($dm^3/s.m.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | mean | max. | min. | s. dev | mean | max. | min. | s. dev |
| Masonry brick /block | Timber | | | | | | | | |
| Caulked | | 0.0014 | | | | 0.6 | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Metal | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Plastic | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Concrete | Timber | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Concrete | Metal | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Concrete | Plastic | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber | Timber | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | 0.05 | 0.06 | 0.05 | | 0.66 | | | |
| Timber | Metal | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber | Plastic | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber/Masonry | Timber | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber/Masonry | Metal | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber/Masonry | Plastic | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

TABLE 6.3.1 AIR LEAKAGE DATA - Timber Doors

(data expressed for each metre length of joint)

| Item | Flow Coefficient ($dm^3/s.m.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev | mean | max. | min. | s.dev |
| **Single side hung - timber** | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Internal | 1.45 | 2.57 | 0.81 | 0.54 | 0.6 | 0.7 | 0.5 | 0.05 |
| External | 0.96 | 1.24 | 0.7 | 0.24 | 0.64 | | | 0.05 |
| Firedoor | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Internal | 1.58 | 3.38 | 0.49 | 0.67 | 0.59 | 0.79 | 0.51 | 0.05 |
| External | 1.32 | 3.52 | 0.79 | 0.55 | 0.59 | 0.71 | 0.50 | 0.05 |
| Firedoor | 1.71 | | | | 0.58 | | | |
| **Single side hung - metal** | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Internal | | | | | | | | |
| External | | | | | | | | |
| Firedoor | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Internal | 0.038 | | | | 0.66 | | | |
| External | 0.038 | | | | 0.66 | | | |
| Firedoor | | | | | | | | |
| **Double side hung - timber** | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Internal | | | | | | | | |
| External | | | | | | | | |
| Firedoor | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Internal | | | | | | | | |
| External | 4.17 | | | | 0.66 | | | |
| Firedoor | 1.95 | | | | 0.6 | | | |
| **Sliding door - timber** | | | | | | | | |
| Weatherstripped: | | | | | | | | |
| Internal | | | | | | | | |
| External | | | | | | | | |
| Unweatherstripped: | | | | | | | | |
| Internal | | | | | | | | |
| External | 0.2 | | | | 0.66 | | | |
| **Roller shutter** (per $m^2$ of door) | 14.0 | | | | 0.66 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

## TABLE 6.3.2 AIR LEAKAGE DATA - Windows

(Data expressed for each metre length of joint)

| Item | Flow Coefficient ($dm^3/s.m.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev. | mean | max. | min. | s. dev. |
| **Casement - side hung** | | | | | | | | |
| **Weatherstripped:** | | | | | | | | |
| Timber | 0.03 | 0.1 | 0.01 | 0.03 | 0.66 | | | |
| Timber clad | 0.17 | | | 0.01 | 0.66 | | | |
| Metal | 0.27 | 0.29 | 0.14 | 0.03 | 0.66 | | | |
| Plastic | | | | | | | | |
| **Unweatherstripped:** | | | | | | | | |
| Timber | 0.23 | 1.19 | 0.04 | 0.2 | 0.66 | 0.85 | 0.50 | 0.1 |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| **Casement - top hung** | | | | | | | | |
| **Weatherstripped:** | | | | | | | | |
| Timber | 0.42 | 1.22 | 0.11 | 0.32 | 0.57 | 0.69 | 0.50 | 0.06 |
| Timber clad | | | | | | | | |
| Metal | 0.32 | 0.55 | 0.18 | 0.15 | 0.6 | 0.64 | 0.52 | 0.04 |
| Plastic | | | | | | | | |
| **Unweatherstripped:** | | | | | | | | |
| Timber | 1.08 | 1.38 | 0.88 | 0.22 | 0.56 | 0.61 | 0.60 | 0.05 |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| **Casement - central pivot vertical** | | | | | | | | |
| **Weatherstripped:** | | | | | | | | |
| Timber | 0.03 | | | | 0.78 | | | |
| Timber clad | | | | | | | | |
| Metal | 0.07 | 0.12 | 0.02 | 0.05 | 0.66 | 0.7 | 0.63 | 0.03 |
| Plastic | | | | | | | | |
| **Unweatherstripped:** | | | | | | | | |
| Timber | | | | | | | | |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| **Casement - central pivot horizontal** | | | | | | | | |
| **Weatherstripped:** | | | | | | | | |
| Timber | 0.02 | | | | 0.57 | | | |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| **Unweatherstripped:** | | | | | | | | |
| Timber | 0.8 | 1.25 | 0.04 | 0.4 | 0.6 | 0.9 | 0.53 | 0.1 |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |
| **Horizontal sliding - single** | | | | | | | | |
| **Weatherstripped:** | | | | | | | | |
| Timber | 0.05 | | | 0.03 | 0.66 | | | |
| Timber clad | 0.06 | | | 0.01 | 0.66 | | | |
| Metal | 0.08 | 0.18 | 0.05 | 0.05 | 0.66 | | | |
| Plastic | | | | | | | | |
| **Unweatherstripped:** | | | | | | | | |
| Timber | 0.13 | | | | 0.66 | | | |
| Timber clad | | | | | | | | |
| Metal | | | | | | | | |
| Plastic | | | | | | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## TABLE 6.3.4 AIR LEAKAGE DATA - Wall/Floor Joints

(Data expressed for each metre length of joint)

| Item Wall Material | Bottom (Foundation) Material | Flow Coefficient ($dm^3/s.m.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|---|
| Masonry brick /block | Sill | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Chipboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Brick+DPC | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Concrete | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber frame panel (plaster wallboard) | Sill | | | | | | | | |
| Caulked | | 0.08 | 0.12 | 0.04 | | 0.66 | | | |
| Uncaulked | | 0.41 | | | 0.1 | 0.66 | | | |
| Timber frame panel (plaster wallboard) | Chipboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | 0.006 | 0.008 | 0.002 | | 0.66 | | | |
| Timber frame panel (plaster wallboard) | Brick+DPC | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber frame panel (plaster wallboard) | Concrete | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | 0.007 | 0.020 | 0.001 | 0.006 | 0.66 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

## TABLE 6.3.5 AIR LEAKAGE DATA - Wall/Ceiling Joints

(Data expressed for each metre length of joint)

| Item Wall Material | Ceiling Material | Flow Coefficient ($dm^3/s.m.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|---|
| Masonry brick /block | Steel beam | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Fibreboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Masonry brick /block | Plasterboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber frame panel (plaster wallboard) | Steel beam | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Timber frame panel (plaster wallboard) | Fibreboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | 0.03 | 0.26 | 0.01 | | 0.66 | | | |
| Timber frame panel (plaster wallboard) | Plasterboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Steel beam | Steel beam | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Steel beam | Fibreboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | | | | | | | | |
| Steel beam | Plasterboard | | | | | | | | |
| Caulked | | | | | | | | | |
| Uncaulked | | 0.05 | | | | 0.67 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## TABLE 6.3.6 AIR LEAKAGE DATA - Wall/Wall Joints

(Data expressed for each metre length of joint)

| Item | Flow Coefficient $(dm^3/s.m.Pa^{2/3})$ | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev | mean | max. | min. | s. dev |
| Timber frame panel to timber frame panel: | | | | | | | | |
| Caulked | | | | | | | | |
| Uncaulked | 0.002 | 0.008 | 0.001 | 0.002 | 0.66 | | | |
| Timber frame panel to masonry brick/block: | | | | | | | | |
| Caulked | | | | | | | | |
| Uncaulked | | | | | | | | |
| Masonry brick/block to timber frame panel: | | | | | | | | |
| Caulked | | | | | | | | |
| Uncaulked | | | | | | | | |
| Masonry brick/block to masonry brick/block: | | | | | | | | |
| Caulked | | | | | | | | |
| Uncaulked | | | | | | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## TABLE 6.3.7 AIR LEAKAGE DATA - Roofs (including joints)

(Data expressed for each $m^2$ of surface)

| Item | Flow Coefficient ($dm^3/s.m^2.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|
| Ceramic tiles: | | | | | | | | |
| Flat | 4.6 | | | | 0.54 | | | |
|  | 4.0 | | | | 0.6 | | | |
| Cement tiles | 4.6 | | | | 0.5 | | | |
| Asbestos cement shingles:  | | | | | | | | |
| Not weatherstripped | 1.08 | | | | 0.9 | | | |
| Weatherstripped | 0.7 | | | | 0.7 | | | |
| Asbestos cement shingles:  | | | | | | | | |
| Not weatherstripped | 0.6 | | | | 0.7 | | | |

## TABLE 6.3.8 AIR LEAKAGE DATA - Exterior Walls (including joints) Timber Frame

(Data expressed for each $m^2$ of surface)

| Item | Flow Coefficient ($dm^3/s.m^2.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|
| Lapped weatherboards: Coated alkyd paint, 18mm | 0.01 | | | | 1.0 | | | |
| Rusticated weatherboards: Unpainted, 18mm thick | $10^{-4}$ | | | | 1.0 | | | |
| Timber frame panels, fibreboard sheathing, rainscreen cladding, plasterboard lining | 0.08 | | | | 0.75 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

## TABLE 6.3.9 AIR LEAKAGE DATA - Exterior Walls (including joints) Bricks

(Data expressed for each $m^2$ of surface)

| Item | Flow Coefficient ($dm^3/s.m^2.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|
| Clay brick, unvented, cavity filled with expanded mica insulation: | | | | | | | | |
| Bare surface | 0.024 | | | | 0.81 | | | |
| 3 coats plaster on inside surface | 0.0014 | | | | 1.0 | | | |
| Clay brick, unvented, cavity filled with granulated mineral wool: | | | | | | | | |
| Bare surface | 0.024 | | | | 0.81 | | | |
| 3 coats plaster on inside surface | 0.0034 | | | | 1.0 | | | |
| Brick, ventilated cavity, glass fibre insulation, vapour barrier, wallboard inside | 0.18 | | | | 0.81 | | | |
| Ditto but cavity air vented | 0.01 | | | | 0.87 | | | |

## TABLE 6.3.10 AIR LEAKAGE DATA - Exterior Walls (including joints) Concrete Blocks

(Data expressed for each $m^2$ of surface)

| Item | Flow Coefficient ($dm^3/s.m^2.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|
| Expanded clay aggregate blocks, hollows empty: | | | | | | | | |
| Bare surface | 0.13 | | | 0.014 | 1.0 | | | |
| 2 coats paint on inside surface | 0.1 | | | | 0.7 | | | |
| Ditto + 2 coats stucco and 1 coat paint on outside surface | 0.04 | | | | 0.85 | | | |
| Expanded clay aggregate blocks, hollows filled with volcanic dust | 0.14 | | | | 0.84 | | | |
| Expanded slag aggregate blocks, hollows filled with expanded mica: | | | | | | | | |
| Bare surface | 0.1 | | | | 0.9 | | | |
| 3 coats stucco on outside surface | 0.1 | | | | 0.8 | | | |
| Sand and gravel blocks, hollows filled with expanded mica: | | | | | | | | |
| Bare surface | 0.016 | | | | 0.9 | | | |
| 1 coat latex paint on inside surface | 0.021 | | | | 0.9 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication.* *See note on page 6.8.*

TABLE 6.3.11 AIR LEAKAGE DATA - Exterior Walls (including joints) Miscellaneous

(Data expressed for each $m^2$ of surface)

| Item | Flow Coefficient ($dm^3/s.m^2.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|
| Precast concrete panels, gasket joints, plasterboard lining | 0.026 | | | | 0.75 | | | |
| Profiled aluminium cladding with bonded composite insulation and lining | 0.24 | | | | 0.75 | | | |
| Profiled steel cladding with separate quilt insulation and plasterboard lining | 0.26 | | | | 0.75 | | | |
| Multi-storey curtain wall | 0.19 | 0.23 | 0.14 | | 0.75 | | | |
| Multi-storey concrete or metal panel | 0.08 | 0.14 | 0.03 | | 0.75 | | | |
| Timber frame and rendered brick | 0.03 | | | | 0.75 | | | |
| Timber frame and brick only | 0.19 | 0.23 | 0.15 | | 0.75 | | | |

TABLE 6.3.12 AIR LEAKAGE DATA - Miscellaneous Components

(Values expressed as a typical value for each component)

| Item | Flow Coefficient ($dm^3/s.Pa^{2/3}$) mean | max. | min. | s. dev | Flow Exponent mean | max. | min. | s. dev |
|---|---|---|---|---|---|---|---|---|
| Chimney | 4.1 | | | | 0.6 | | | |
| Open fireplace, brick chimney | 17.0 | | | | 0.5 | | | |
| Fireplace with 100mm diameter flue | 6.2 | | | | 0.5 | | | |
| Fireplace without insert: | | | | | | | | |
| Damper open | 45.2 | 49.0 | 41.0 | | 0.5 | | | |
| Damper closed | 8.9 | 10.8 | 7.0 | | 0.5 | | | |
| Fireplace with insert: | | | | | | | | |
| Damper open | 8.4 | 11.6 | 5.2 | | 0.5 | | | |
| Damper closed | 4.7 | 5.9 | 3.4 | | 0.5 | | | |
| Fireplace, damper closed | 8.3 | 17.9 | 1.9 | | 0.5 | | | |
| Mail slot | 0.2 | | | | 0.5 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

## TABLE 6.3.13 AIR LEAKAGE DATA - Penetrations - Ducts

**(Values expressed as a typical value for each component)**

| Item | Flow Coefficient ($dm^3/s.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev | mean | max. | min. | s. dev |
| Duct through exterior wall | 2.5 | | | | 0.66 | | | |
| Duct through internal wall | 0.44 | | | | 0.66 | | | |
| Flue vent through ceiling | 3.0 | | | | 0.66 | | | |
| Spiral duct, 180mm diameter: | | | | | | | | |
| Poor seal | 0.44 | | | | 0.66 | | | |
| Well sealed with polyurethane foam | 0.015 | | | | 0.66 | | | |

## TABLE 6.3.14 AIR LEAKAGE DATA - Penetrations - Pipes

**(Values expressed as a typical value for each component)**

| Item | Flow Coefficient ($dm^3/s.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev | mean | max. | min. | s. dev |
| Conduit, 15mm diameter: | | | | | | | | |
| Well sealed | 0.0 | | | | | | | |
| Through cross-cuts in vapour barrier | 0.19 | | | | 0.66 | | | |
| Pipe through wall | 0.62 | | | | 0.66 | | | |
| Opening for pipe or duct: | | | | | | | | |
| Caulked | 0.06 | | | | 0.66 | | | |
| Not caulked | 0.31 | | | | 0.66 | | | |
| Plumbing to bath | 2.9 | | | | 0.66 | | | |
| Discharge pipe: | | | | | | | | |
| 19mm diameter | 0.06 | | | | 0.66 | | | |
| 38mm diameter | 0.17 | | | | 0.66 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

## TABLE 6.3.15 AIR LEAKAGE DATA - Penetrations - Electrical Outlets

(Values expressed as a typical value for each component)

| Item | Flow Coefficient ($dm^3/s.Pa^{2/3}$) | | | | Flow Exponent | | | |
|---|---|---|---|---|---|---|---|---|
| | mean | max. | min. | s. dev | mean | max. | min. | s. dev |
| Electrical wall outlet | 0.25 | 0.46 | | | 0.66 | | | |
| Electrical wall outlet: | | | | | | | | |
| With gasket | 0.01 | | | | 0.66 | | | |
| Electrical wall outlet, carefully fitted: | | | | | | | | |
| Cable holes open | 0.08 | | | | 0.66 | | | |
| Cable holes plugged | 0.05 | | | | 0.66 | | | |
| Electrical switch | 0.06 | | | | 0.66 | | | |
| Duplex outlet: | | | | | | | | |
| In insulated wall | 0.31 | | | | 0.66 | | | |
| In uninsulated wall | 0.36 | | | | 0.66 | | | |
| Electrical box in exterior wall: | | | | | | | | |
| With gasket | 0.08 | | | | 0.66 | | | |
| Without gasket | 0.21 | | | | 0.66 | | | |
| Recessed light fitting: | | | | | | | | |
| Uncaulked | 1.04 | | | | 0.66 | | | |
| Caulked round edges | 0.21 | | | | 0.66 | | | |
| Recessed spotlight | 0.99 | | | | 0.66 | | | |
| Side mounted light | 0.12 | | | | 0.66 | | | |
| Ceiling mounted lights | 0.08 | | | | 0.66 | | | |

*Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication. See note on page 6.8.*

## 6.4 GLOSSARY

adventitious opening
An opening in the building envelope which is unintentional.

air change
A quantity of fresh air equal to the volume of the room (building) being ventilated. (SI unit $m^3$).

air change rate
The ratio of the volumetric rate at which air enters (or leaves) a room divided by the volume of the room. Usually this is expressed in air changes per hour (ach). (SI unit $h^{-1}$).

air distribution
The delivery of outdoor or conditioned air to various spaces in a building, usually by mechanical means.

air exchange
see "air change"

air flow
The mass/volume transport of air between two points. Flow is usually further categorised by whether it is laminar or turbulent.

air flow rate
The mass/volume of air moved in unit of time. (The transport may be within an enclosure or through an enclosing envelope).
(SI units: kg/s - mass flow rate, $m^3/s$ - volume flow rate)

air infiltration
The uncontrolled inward air leakage through cracks and interstices in any building element and around windows and doors of a building, caused by the pressure effects of the wind and/or the effect of differences in the indoor and outdoor air density.

air infiltration characteristic
The relationship between the flow rate of air infiltration into a building and the parameters which cause the movement.

air inlet
Opening in a building envelope or room wall for the provision of outdoor or conditioned air.

air leakage
The flow of air through a component of the building envelope, or the building envelope itself, when a pressure difference is applied across the component.

air leakage characteristic

An expression which describes the air leakage rate of a building or component. This may be:

(a) the air leakage flow rate at a reference pressure difference across the component or building envelope.

(b) the relationship between flow rate and pressure difference across the building envelope or component

(c) the Equivalent Leakage Area at a reference pressure difference across the component or building envelope.

air outlet

Opening in a building envelope or shaft through which vitiated air is expelled to the outside.

air renewal

The process of replacing vitiated indoor air by outdoor or conditioned air.

air quality (indoor)

The time-weighted mean concentration of airborne pollutants.

Note: The time period is normally 8, 24 or 40 hours and must be stated.

(SI unit $\mu g/m^3$).

airtightness

A general descriptive term for the leakage characteristics of a building.

Note: The smaller the leakage rate at a given pressure difference across a building envelope, the greater the "airtightness".

airtight building

A building which is (relatively), (a) impervious to air, (b) resistant to penetration by air.

air-to-air heat recovery

The process by which heat from outgoing warm vitiated air is transferred to incoming cool outdoor air with minimal mixing between the two air streams.

airtightness standard

Standard value of building or component air leakage corresponding to a reference pressure difference across the building envelope or component. Standard values may be expressed in terms of air change rate, flow rate per unit area of opening, or flow rate per unit length of crack.

backdraughting

The reverse flow of polluted air (or flue gases) in a chimney, flue or other air outlet.

blower door
A device that fits into a doorway for supplying or extracting a measured flow rate of air to or from a building. It is normally used for testing for air leakage by pressurization or depressurization.

building envelope
The total of the boundary surfaces of a building through which heat (or air) is transferred between the internal spaces and the outside environment.

caulking
To make a joint airtight by applying a sealing material. A form of weatherstripping. See also "weatherstripping".

commercial building
A functional classification term for buildings. A general term for buildings whose primary purpose is to provide space for commercial rather than domestic activity.

component leakage
The leakage of air through the building envelope which is directly attributable to flow through cracks around doors, windows, etc.

component opening
Crack, vent or other opening formed in the building envelope which is directly attributable to particular components such as doors, windows, ventilation bricks, etc.

constant concentration measurement
See "tracer gas (constant concentration method)".

constant flow measurement
See "tracer gas (constant flow (emission) method)".

constant emission measurement
See "tracer gas (constant flow (emission) method)".

contaminant
An unwanted airborne constituent that may reduce the acceptability of the air.

cost effectiveness
Consideration of the financial gains, assessed over an agreed period, effected by a change compared with the expense of achieving the proposed change. A change is said to be cost effective if the financial gains exceed the expense.

cross contamination (of air)
The contamination of one stream (or mass) of air by pollutants in another due to air movement between the two streams (or masses).

decay method

See "tracer gas (rate of decay method)".

degree day

The number of degrees of temperature difference on any one day between a given base temperature and the 24-hour mean outside air temperature for the particular location.

depressurisation

The term used in connection with building/component air leakage tests when the pressure inside a building (or on the indoor surface of a component) is maintained at a level lower than the pressure outside (or on the outside surface of a component).

discharge coefficient

A dimensionless coefficient relating the mean flow rate through an opening to an area and the corresponding pressure difference across the opening.

draught

Excessive air movement in an occupied enclosure causing discomfort.

equivalent leakage area (ELA)

The equivalent amount of orifice area that would pass the same quantity of air as would pass collectively through the building envelope at a specified reference pressure difference.

exfiltration

The uncontrolled flow of air out of a building.

extract air

exhaust air that is discharged to the atmosphere from a building.

flow characteristic

A term embracing the various relevant constants, coefficients and exponents in an expression governing flow.

flow coefficient (k)

Parameter used in conjunction with the "flow exponent" to quantify flow through an opening.

flow equation

Equation describing the air flow rate through a building (or component) in response to the pressure difference across the building (or component).

flow exponent (n)

Parameter characterising the type of flow through a component. (n=1 represents laminar flow, n=0.5 represents turbulent flow). For many openings, n takes a value between these extremes.

flow (laminar)
Flow in which fluid moves smoothly. In this flow form, cross stream momentum transfer takes place by viscous action alone and mixing between flow strata does not occur.

flow (mass balance)
Equilibrium condition in which mass flow into a space balances that which is leaving.

flow network
A network of zones or cells of differing pressure connected by a series of flow paths.

flow (orifice)
Flow through an opening which may be considered to conform to the laws governing fully turbulent flow through an orifice.

flow (piston)
See "flow (plug)"

flow (plug)
The type of flow in which fluid is displaced without mixing e.g. the displacement of contaminated air by fresh air.

flow (turbulent)
Flow in which cross-stream momentum transfer is dominated by bulk motion of the fluid in the form of random eddies.

fresh air
See "outdoor air".

gap leakage
See "component leakage".

heat exchanger (air-to-air)
A device designed to transfer heat from two physically separated fluid streams. In buildings, it is generally used to transfer heat from exhaust warm air to incoming cooler outdoor air.
See "air-to-air heat recovery"

heat pump (air-to-air)
A device operating on a refrigeration cycle in which both evaporator and condenser are refrigerant/air heat exchangers. As a heating season heat recovery device, the evaporator transfers heat from the exhaust warm air to the refrigerant and the condenser transfers heat from the refrigerant to incoming cooler outdoor air. Arrangements are often made to allow the refrigerant flow to be reversed making the condenser the evaporator and vice versa - thus heat may be recovered in the cooling season.

heat pump (air-to-water)
A device operating on a refrigeration cycle in which the evaporator is a water/refrigerant heat exchanger and the condenser a refrigerant/air heat exchanger. The circuit normally includes an arrangement which allows the refrigerant flow to be reversed thus allowing heat to be transfered in either direction. In one system, a number of small air/water heat pumps installed in various zones around a building are used to transfer heat into or from a common water circuit. Thus heat unwanted in one zone may be transferred to another where it is needed.

heat pump (exhaust air)
See "heat pump (air-to-air)".

heat recovery
See "heat exchanger" and "air-to-air heat recovery"

heat recovery effectiveness
See "heat recovery efficiency".

heat recovery efficiency
The proportion, normally expressed as a percentage, of heat recovered from otherwise "waste heat", passing through a heat recovery system.

indoor climate
The synthesis of day-to-day values of physical variables in a building, e.g. temperature, humidity, air movement and air quality, etc., which affect the health and/or comfort of the occupants.

industrial building
A functional classification term for buildings of which the main purpose is to provide space for manufacturing and assembly processes. These are characterised by high levels of activity, both mechanical and human, and often by generation of internal pollution.

infiltration degree day
A measure of severity of the climate as it relates to air infiltration.

infiltration heat loss
Heat loss from a building which is directly attributable to the effects of cooler outside air leaking into a building and of warm air leaking out.

intentional opening
See "purpose provided opening".

iterative method
Method of computation in which a solution compatible with the known facts emerges following a series of calculations made by ascribing values, successively changed by small steps, to the unknown variable(s). This method, often too tedious to undertake manually, becomes practicable using computers.

leakage (area)
The actual open area of a hole or gap.

leakage (background)
Leakage of air through a building envelope which is <u>not</u> accounted for by obvious measurable gaps, i.e. component or purpose provided openings.

leakage (components)
See "component leakage".

leakage distribution
The apportionment of air leakage through the openings (flow paths) comprising the flow network.

leakage (fabric)
See "leakage (background)".

mixing (imperfect)
The combining of two or more substances such that the parts of one are unevenly distributed among the parts of another.

mixing (perfect)
See "mixing (uniform)".

mixing (uniform)
The combining of two or more substances such that the parts of one are wholly diffused throughout the parts of another.

multizone
A building or part of a building comprising a number of zones or cells.

network model
See "theoretical model (network method).

network technique
Theoretical method for estimating the magnitude of air infiltration and interzone air movement using a model which considers a building to comprise a number of enclosed spaces each at its own internal pressure.

network technique (single cell)
Theoretical method for estimating the magnitude of air infiltration, using a model which considers a building as a single enclosed space at a single internal pressure.

neutral pressure plane
A horizontal plane where no (mean) pressure difference exists between the inside and outside of a building.

occupancy
The time during which occupants are in a building (generally expressed as hours per day).

occupancy pattern
The form and type of activity of occupants whilst in a building.

open area
The actual physical area of an opening in a building.

opening (large)
Opening (hole, gap) in a building envelope which is generally purpose made, e.g. door, window, vent, etc.

opening (orifice)
That size of opening in the form of a single orifice which would be required to represent the sum of all leakage openings in a building envelope such that, for a given applied pressure difference across it, the rate of air flow through the orifice would be identical to that applicable to the building itself for the same pressure difference.

outdoor air
Air from free atmosphere that is generally assumed to be sufficiently uncontaminated to be used for ventilation.

payback
The financial gain, accumulated over a period, arising from the introduction of a certain measure after deducting the initial cost of the measure and all operating and maintenance costs attributable to it over the same period. In making the comparison, account is taken of interest rates, inflation rate, energy cost inflation (as appropriate) and all costs and savings discounted to adjust them to a common date (generally the present day).

pollutant concentration
The concentration in air of contaminants such as noxious gases or dust particles.
Note: Concentrations are often expressed as time weighted values over 24 hours, a working day or working week.
(SI unit µg/m3).

power law equation
The relationship governing the air flow rate through a building or component which is expressed in the form of a power law.

pressure coefficient
A dimensionless coefficient relating the velocity pressure on the outer surface of a building to the velocity pressure derived from the mean wind velocity at a reference point.

pressure distribution (internal)
The pattern of static pressure variation at various points inside a building due to variations in air density and air flow into and out of the building.

pressure distribution (surface)
The pattern of positive (or negative) pressure relative to the static pressure of the prevailing free wind, at various points on the external surface of a building, caused by the flow of the wind onto or around a building.

pressure (stack)
Pressure differential across a building caused by differences in the density of the air due to an indoor-outdoor temperature difference.

pressure (static)
The pressure exerted on its surroundings by a volume of fluid.
(SI unit Pa).

pressure (total)
The algebraic sum of the static pressure and the velocity pressure at a point.

pressurisation
A method of testing for air leakage of a building or component by installing a fan in the building envelope, e.g. through a door or window, and creating a static pressure excess inside the building. The flow rate through the fan and pressure difference across the envelope are measured and air leakage assessed.

purpose provided opening
Opening in the building envelope for the specific purpose of supplying ventilation air, i.e. air bricks, vents, extractor fans, intake and exhaust for HVAC systems, chimneys, etc.

quadrature
The name given to the arithmetical process whereby the sum of two values is given by the square root of the sum of the squares of the two values.

reference pressure
A specified pressure to which pressure dependent quantities may be adjusted to facilitate comparison of magnitudes.
Note: (a) The CIBSE reference absolute pressure for air is 101.325 kPa.
(b) Flow coefficients in the exponential form of the leakage equation are usually flow rates at a reference pressure difference of 1 Pa.

regression method
Method of investigating the functional dependence of variables on each other. It consists of estimating regression coefficients applied to the various terms in the empirical equation approximating the functional relationship.

retrofit
The process of reducing energy loss in an existing building by physical means, e.g. reducing excess air infiltration by obstructing flow through cracks and openings.

roughness (terrain)
See "terrain roughness".

shelter belt
See "windbreak".

shielding
The degree of protection from wind offered to a building by upstream obstacles. These may be windbreaks, shelter belt, or another building. It may be negative where eddy reinforcement takes place between large buildings.

shielding class
Classification for the degree of shielding by local obstacles, ranging from Class I (shielding coefficient 0.34) to Class V (shielding coefficient 0.11).

shielding coefficient
The ratio of average total exterior wind pressure to the stagnation pressure at ceiling height.

short circuiting
Direct flow between an inlet and outlet, i.e. along shortest path, without mixing

single zone
A building or part of a building comprising one zone of uniform pressure.

specific leakage area
Leakage area expressed per unit floor area.

stack
A single chimney/flue or a cluster of chimneys/flues.

stack effect
The pressure differential across a building caused by differences in the density of the air due to an indoor-outdoor temperature difference.
See "pressure (stack)".

stack infiltration
Infiltration driven by stack effect.

stack pressure
See "pressure (stack)".

stagnation pressure (at ceiling height)
The sum of the velocity pressure due to the wind and the absolute pressure if there were no wind.
Note: The velocity pressure to be used is that calculated using the wind speed at ceiling height, which would be measured if the structure was not present.

stratification
The formation of layers of different density in a body of fluid which is not well mixed. In the case of a fluid within an enclosure, the variation in density may be due to difference of temperature. The term "thermal stratification" is often ascribed to this condition.

supply air
Air introduced into a treated space by a ventilation system.

terrain class
Measure of surface roughness.

terrain effect
The effect of the landscape surrounding a building on the wind speed and direction, and thus on the surface pressure distribution on the building envelope.

terrain roughness
The character of the terrain over which wind passes upstream of a building causing the wind velocity to be modified. It is common practice to classify terrain according to roughness and express the variation in terms of roughness constants.

theoretical model (network method)
Model of a building employed in network method which include the parameters:
- flow path distribution and characteristics.
- building height.
- internal/external temperature difference.
- local wind speed and external pressure distribution.
- characteristics of mechanical ventilation system.

thermal buoyancy
The upward force experienced by a body of fluid at a higher temperature than the fluid which surrounds it.

thermal stratification
See "stratification".

tracer gas
A gas used with a detection device to determine the rate of air interchange with a space.

tracer gas (constant concentration method)
A method of measuring ventilation rate whereby an automated system injects tracer gas at the rate required to maintain the concentration of tracer gas at a fixed, predetermined level. The ventilation rate is proportional to the rate at which the tracer gas must be injected.

tracer gas (constant flow/emission method)
A method of measuring ventilation rate whereby tracer gas is emitted continuously at a uniform rate. The equilibrium concentration of tracer gas in air is measured.

tracer gas (rate of decay method)
A method of measuring ventilation rate whereby a quantity of tracer gas is released and the decrease in concentration measured as a function of time.

tracer gas technique
General term applied to any method employing tracer gases to determine air infiltration and ventilation rates.

tracer gas (transfer index method)
A method of measuring ventilation rate by determining the transfer index between two points. The time integral of tracer gas concentration is determined at one point following the liberation of a fixed volume of tracer at another. Several sample points are usually employed. The reciprocal of the transfer index has dimensions of ventilation rate.

turbulent fluctuation
Fluctuation in wind induced pressures on a building due to the variable velocity of atmospheric wind.

unintentional opening
See "adventitious opening".

vapour barrier
A moisture-impervious layer applied to the surfaces enclosing a space or to the external surface of thermal insulation to limit moisture migration.

vent
A device permitting air flow in order to maintain the balance of pressure between the atmosphere and the system.

ventilation
The process of supplying and removing air by natural or mechanical means to and from any space.

ventilation effectiveness
An expression describing the ability of a mechanical (or natural) ventilation system to remove pollution originating in a space, either of a steady state or transient nature.

ventilation efficiency (absolute)
A quantity which expresses the ability of a ventilation system to reduce a pollution concentration relative to the feasible theoretical maximum performance.

ventilation efficiency (relative)
A quantity describing how the ventilation ability of a system varies between different parts of a room.

ventilation heat gain/loss
The heat gained or lost by virtue of warm and/or humid air flowing into or leaking from a space.

ventilation (intentional)
Ventilation provided by mechanical systems or through purpose provided openings, e.g. windows, air bricks, etc.

ventilation (purpose provided)
Ventilation provided to a space as the result of specific action to ensure its introduction. Such ventilation may be provided by natural means through purpose provided openings of the required size and position or by mechanical means.

ventilation strategy
A plan by which ventilation air is purposefully provided to a space rather than to rely on the vagaries of adventitious ventilation. When such a strategy is employed it is normal to take action to minimise background leakage.

ventilation system (balanced supply/extract)
A system in which fans both supply and extract air from the enclosed space. Such a system allows air-to-air heat recovery.

ventilation system (mechanical)
A system in which the motive force needed to introduce air to, or extract air from, a space, is provided by one or more fans.

ventilation system (mechanical extract)
A mechanical ventilation system in which air is extracted from a space(s) so creating an internal negative pressure. Supply air is drawn through adventitious or purpose provided openings. Such a system allows heat to be recovered from the extracted air.

ventilation system (mechanical supply)
A system in which air is supplied to a space(s) so creating an internal positive pressure. Air leaves the building through adventitious or purpose provided openings. Such a system does not allow heat to be recovered from the exhausted air.

ventilation (natural)
Ventilation using only natural forces such as wind pressure or differences in air density.

weatherstripping
(a) Fixing a strip of flexible material to seal a joint between a moveable component and its seating. The strip is attached to one edge and excludes air by pressing tightly against the other.
(b) Fixing a piece of material to stop a draught passing the joints of a closed component (such as a door or window).

windbreak
A barrier designed to obstruct wind flow and intended for protection against excessive wind pressure. An example might be a natural or planned barrier of trees or shrubs known as a shelter belt.

wind infiltration
Infiltration driven purely by wind induced pressure differences across a building envelope.

window (openable)
A glazed opening in a wall to let in light in which all or part of the glazing may temporarily be moved to allow the passage of air.

wind regime
The range of weather conditions for which air infiltration is dominated by the effect of wind.

wind speed (meteorological)
The wind speed registered at the nearest meteorological station to the site of the building, presented as the wind speed at a height of 10m in open flat country. (SI unit m/s).

wind speed (profile)
The relationship between wind speed at a reference level, measured wind speed at height (h) and terrain roughness. Generally stated as a power law.

wind speed (reference level)
Wind speed adjusted to a specified height above the ground before use in calculations. (In many instances, as in this publication, the building height is taken as reference level).

wind tunnel (environmental)
A device for simulating the wind speed and turbulence profiles in the lower atmospheric boundary layer for modelling pressure forces on buildings and the patterns of flow around them.