Natural ventilation in non-domestic buildings

CIBSE Applications Manual AM10

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Cover illustration: Bedales School Theatre, Hampshire (courtesy of Feilden Clegg Bradley Architects; photo: Dennis Gilvert)

Note from the publisher

This publication is primarily intended to provide guidance to those responsible for the design, installation, commissioning, operation and maintenance of building services. It is not intended to be exhaustive or definitive and it will be necessary for users of the guidance given to exercise their own professional judgement when deciding whether to abide by or depart from it.

Foreword

The need for the Institution to provide professional guidance on the design and application of natural ventilation in buildings was first identified when I was CIBSE President in 1992. The resulting Applications Manual was first published in 1997 with the aim of 'providing more guidance on energy related topics in order to realise quickly the improvements in energy efficiency which should arise from the application of the guidance presented'.

Much has happened since 1997 in relation to energy use in buildings. The Energy Efficiency Best Practice Programme which sponsored the first edition has been replaced by the Carbon Trust, which has become very widely recognised for its high profile campaigns raising awareness of business use, and waste, of energy. Part L of the Building Regulations, *Conservation of Fuel and Power*, has been transformed and will shortly be revised once more as Part L (2005). The Energy Performance in Buildings Directive has been adopted by the EU, and will be implemented in the UK from the start of 2006. And, late in 2004, the Sustainable and Secure Buildings Act reached the statute book, to enable Building Regulations to address these two, sometimes conflicting, themes.

In the light of all these changes, as well as the growing practical experience of advanced naturally ventilated buildings, it is timely to issue a revised edition of this guidance. The principles remain largely unchanged — as do the laws of physics on which they depend. However, experience in their application has advanced, and new examples have appeared. As a result, the material has been re-ordered, and the examples, instead of standing alone at the end, are now incorporated within the guidance at appropriate places. This edition also draws extensively on work funded by the Partners in Innovation scheme of the DTI on automatic ventilation devices. The guidance contained within this edition will enable practitioners to apply the principles of natural ventilation based on a sound understanding of their underlying basis. In so doing further improvements in energy efficiency will be achieved.

The revision has been undertaken by one of the original authors, Steve Irving, aided by David Etheridge and Brian Ford of Nottingham University. The revision has again been steered by a small group of leading practitioners from a range of professional backgrounds, with the aim of producing guidance that is as far as possible accessible to architects and engineers alike, and will assist them in adopting an integrated approach to building design. The Institution would like to thank the Steering Group, listed below, for their contribution to the project, and also to acknowledge the support of the Carbon Trust for the work.

Brian Moss
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Acknowledgements

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Contents

Natural ventilation in non-domestic buildings

1   Introduction

1.1   General

This publication is a major revision of the Applications Manual first published in 1997[1]. At that time, there was a significant expansion of interest in the application of engineered natural ventilation to the design of non-domestic buildings. The original AM10 sought to capture the state of knowledge as it existed in the mid-nineties and present it in a form suited to the needs of every member of the design team.

Some ten years on from the time when the initial manual was conceived, the state of knowledge has increased, and experience in the design and operation of naturally ventilated buildings has grown. This revision of AM10 is therefore a timely opportunity to update and enhance the guidance offered to designers and users of naturally ventilated buildings.

The first edition of AM10 devoted its first section to setting natural ventilation into the context of the range of available design solutions. This aspect is now dealt with in CIBSE Guide B2: *Ventilation and air conditioning*[2]. The Guide sets out the various approaches to ventilation and cooling of buildings, summarises the relative advantages and disadvantages of those approaches and gives guidance on the overall approach to design. This edition of AM10 is intended to complement Guide B2 by providing more detailed information on how to implement a decision to adopt natural ventilation, either as the sole servicing strategy for a building, or as an element in a mixed-mode design[3].

This edition of AM10 should also be considered alongside other major sources of relevant guidance, and in particular those in support of the requirements of the Building Regulations. For England and Wales, the key documents are:

—   Approved Document F1: *Means of ventilation*[4]

_   Approved Document L2: *Conservation of fuel and power in buildings other than dwellings*[5].

At the time of writing (January 2005), both these parts of the Regulations are the subject of major review, and so the guidance in this document will need to be interpreted in the light of the requirements prevailing at the time of use. CIBSE Guide A[6] complements the guidance in Approved Document F, and provides much fundamental data on minimum ventilation rates and thermal comfort criteria.

1.2   Structure of this publication

Following this introduction, the manual is divided into three main sections. These chapters progress from a review of the strategic issues to a detailed development of design techniques. As such, the material becomes increasingly technical in scope. Consequently, non-technical readers will probably wish to concentrate on section 2, which deals with developing the design strategy. Section 3 deals with a review of ventilation components and how they should be integrated into an overall design philosophy. This section will be particularly relevant to all members of the design team, and elements of it will be relevant to the client and the facilities management team. Section 4 concentrates on design calculations, and is primarily targeted at the building services engineer who has responsibility for engineering the design. Brief overviews of the chapters are provided in the following sections so that readers can identify the material that will be relevant to their own requirements.

1.2.1   Section 2: Developing the design strategy

This section focuses on the strategic issues. It begins by summarising what functions natural ventilation can deliver, and the key issues that need to be considered as part of delivering a successful design. The section contains a detailed flow chart that can be used to assess the viability of natural ventilation.

Natural ventilation systems are intended to provide sufficient outside air to achieve appropriate standards of air quality and to provide cooling when needed. Since the cooling capacity of natural ventilation is limited, a key design challenge is to limit heat gains through good solar control and careful management of the internal gains. The section explains how naturally ventilated buildings do not aim to achieve constant environmental conditions, but take advantage of dynamics to provide comfortable, controllable conditions for the occupants.

The section continues by reviewing the different types of ventilation strategy. The most appropriate strategy is shown to depend on the type of space (i.e. open plan, cellular) and whether wind or buoyancy forces are likely to predominate. The section aims to provide a conceptual understanding of how the various system concepts work, and how different design features can enhance the flexibility and robustness of the design.

Because of the increase in summertime temperatures caused by global warming, the achievement of good thermal comfort with low energy consumption will become increasingly challenging for all summer cooling strategies (both natural and mechanical). The effective application of natural ventilation will increasingly require

careful integration with other design measures (both passive and active), especially in the south-east of England. Global warming does not mean that the importance of natural ventilation diminishes; it will still have a very important role to play as part of an integrated design approach, as a key element in a mixed mode building, and as the lead strategy in the cooler parts of the UK. In addition, it might be the case that, as the climate warms, occupants will adapt themselves to that changing climate, and so the threshold at which people find conditions too warm will also increase.

1.2.2   Section 3: Ventilation components and system integration

This section is mainly about tactics. Having used section 2 to develop the strategy, this section looks at the selection and specification of the various types of ventilation component (i.e. windows, ventilators and dampers) and how they should be integrated into an overall system.

As well as considering the technical issues of design and specification, the section also discusses the important 'softer' issues, such as the division of responsibility between members of the design team and the component suppliers and system installers. This is particularly important since many issues relating to the successful implementation of natural ventilation cross traditional boundaries of design responsibility.

Another key issue is the inter-relationship between the system and the occupants. A key aspect of natural ventilation is to empower the occupant to make suitable adjustments to window opening etc. to maintain personal comfort without prejudicing the comfort of others. This means that automatic control strategies need to be carefully integrated with user behaviour. Such issues are developed in section 3.

Because of the important link between the design and the way the user operates the building, section 3 stresses the benefits of post-completion fine tuning to ensure the full potential of the building is being realised to the benefit of the occupants.

1.2.3   Section 4: Design calculations

Section 4 is the most technical part of the manual. It begins by reviewing the calculations that will need to be carried out and reviews the type of calculation techniques that are available.

The section suggests that for basic design purposes, a class of tools known as 'explicit envelope flow models' are the most appropriate. They allow basic dimensioning of the system components. It then explains how other, more sophisticated tools (such as implicit envelope flow models, combined thermal and ventilation models, computational fluid dynamics and physical scale models) can be used to check the performance of the sized system under a variety of operating modes.

Because implicit envelope flow models are the most useful tool to the designer, this aspect is developed in depth, showing how the basic textbook equations can be manipulated to provide solutions to most design problems. These techniques are then illustrated with a number of worked

examples, and guidance on where the relevant input data might be found.

As an adjunct to this manual, a spreadsheet tool* has been prepared that implements many of the design calculations included in section 4. This is intended as an illustration of how the methods could be implemented. Users will need to confirm that the tool meets their own requirements, and adjust it as necessary to meet the particular circumstances of the design issue they are investigating.

2   Developing the design strategy

2.1   Satisfying design requirements

Natural ventilation is one of a number of strategies that are available to the designer. CIBSE Guide B2[2] contains an overview of the various approaches and gives guidance on their applicability to different situations.

Natural ventilation systems need to be designed to achieve two key aspects of environmental performance:

—   ventilation to maintain adequate levels of indoor air quality

—   in combination with other measures, ventilation can reduce the tendency for buildings to overheat, particularly in summer.

The natural ventilation strategy must also be integrated with all other aspects of the building design. Key issues for consideration are:

—   *A satisfactory acoustic environment*: natural ventilation openings also provide a noise transmission path from outside to inside, and this may be a determining factor in some building locations. In addition, naturally ventilated buildings often include large areas of exposed concrete in order to increase the thermal capacity of the space. Such large areas of hard surface will require careful attention to achieve a satisfactory internal acoustic environment.

—   *Smoke control*: since smoke can follow natural ventilation paths, the integration of the fire safety strategy must be an important part of design for natural ventilation.

—   *Health and safety*[7]: many natural ventilation openings will be at significant heights above floor level and so the proposed Work at Heights Regulations[8] will be particularly relevant.

2.1.1   Ventilation

The principle role of ventilation is to provide an appropriate level of indoor air quality (IAQ) by removing and diluting airborne contaminants. Guidance on achieving adequate levels of IAQ (to avoid mould growth and health hazards) is given in Approved Document F[4]. Higher rates of ventilation may be provided than proposed in the

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Approved Document, and this may enhance the perception of freshness, but in most cases this will come at a price because energy costs will increase correspondingly. In order to achieve adequate IAQ, Approved Document F adopts a three-stage strategy as follows

(*a*)   *Extract ventilation*: to remove pollutants at source, with the extracted air being replaced with outside air.

(*b*)   *Whole-building ventilation (supply and extract)*: to disperse and dilute other pollutants.

(*c*)   *Purge ventilation*: to aid removal of high concentrations of pollutants released from occasional activities such us painting, or the accidental release via spillages etc. Purge ventilation is typically an order of magnitude greater than background ventilation. As well as helping to remove high levels of contaminants, purge ventilation can also help to remove excess heat from the space, thereby assisting thermal comfort in summer.

The whole-building ventilation rate recommended by both the 2005 edition of CIBSE Guide A[9] and the draft Approved Document F[10] is 10 litre·s^{-1} per person. This is based on the correlation between ventilation rates and health. Since naturally ventilated buildings cannot provide a constant ventilation rate, it is necessary to demonstrate that an equivalent level of air quality has been provided. This can be done by showing that the IAQ achieved by the natural ventilation is equivalent to that provided using a constant ventilation rate of 10 litre·s^{-1} per person during occupied hours. One way of doing this is to use the CO_2 level in the space as a proxy for general IAQ levels. By calculation, the CO_2 levels in the occupied space can be determined based on a constant ventilation rate of 10 litre·s^{-1} per person during occupied hours. A similar calculation can then be carried out using the variable ventilation rate typical of a naturally ventilated scheme. In both cases, the boundary conditions of external CO_2 concentration, occupancy levels etc. must be the same. The naturally ventilated design would be acceptable if the average CO_2 concentration during occupied hours is no greater than that achieved by the mechanically ventilated design, and the maximum concentration in the naturally ventilated scheme is never greater than an agreed maximum threshold figure. The IAQ tool in the spreadsheet (see section 1.2.3) illustrates how these calculations can be carried out. This is illustrated in Figure 2.1.

Figure 2.1(a) shows the CO_2 profile for a constant ventilation rate of 10 litre·s^{-1} per person (equivalent to 1.2 ACH in this example), coupled with a background infiltration rate of 0.1 ACH. Figure 2.1(b) shows a naturally ventilated scheme having three levels of ventilation: a night-time rate of 0.25 ACH, an initial daytime rate of 1.0 ACH and a boosted rate in the middle of the day of 1.5 ACH. The average concentration of CO_2 in the two cases is 986.2 and 971.9 ppmv respectively although, as can be seen, the natural ventilation peaks at just over 1100 ppmv, compared to the constant mechanical case of 1005 ppmv.

In a similar way, if the volume of the space is sufficiently large, then the pollutants from the activities in the space will only degrade the IAQ in the occupied zone slowly, especially if a pure displacement type ventilation strategy is adopted, with the pollutants being concentrated in a stratified layer above occupant level. As an illustration, consider ventilating a theatre, where there the design occupancy is 1000 people. This occupancy will only last for the duration of the performance, but will build up to that peak for the hour or two preceding 'curtain-up'. Figure 2.2 shows the evolution of CO_2 concentration in the space when ventilating at a constant rate between 17:00 to 22:00 equivalent to 8 litre·s^{-1} per person based on
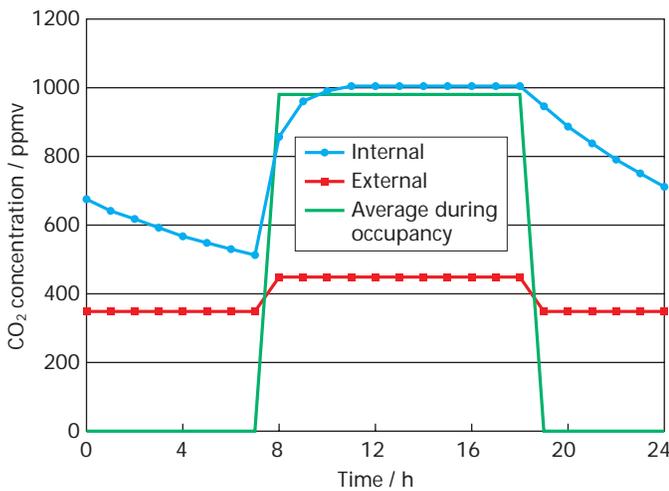
(a) Constant mechanical ventilation rate
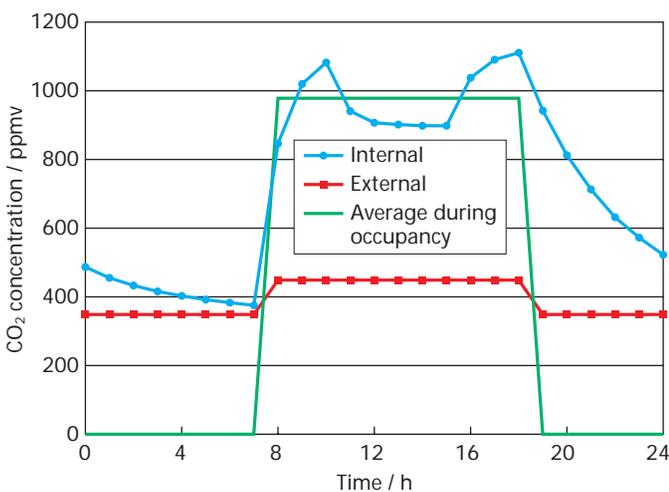
(b) Varying natural ventilation rate

Figure 2.1 Comparison of constant and variable ventilation rates on indoor air quality
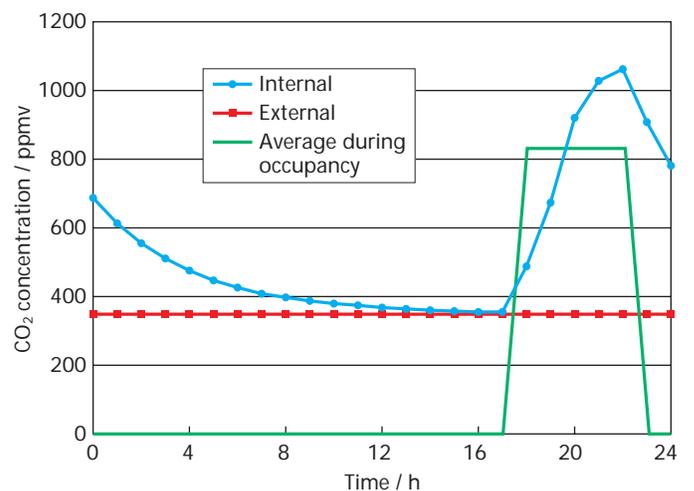

Figure 2.2 Effect of volume and airtightness on indoor air quality

the design occupancy. This is 20% less than the whole-building ventilation rate recommended by Approved Document F[4] but the average concentration in the space peaks just above 1000 ppmv at the end of the performance. If a displacement flow regime is in place, then the concentration in the occupied zone will be significantly lower. This relatively simple example illustrates the importance of the dynamics of ventilation.

2.1.1.1   Control of ventilation

If natural ventilation is to be adopted, then the system has to be able to provide controllable ventilation rates across a wide range, from say 0.5 to 5 ACH or even more. Indeed, it should be possible to shut down the ventilation rate to near zero when the building is unoccupied, especially if occupancy is the principal source of pollutants. The wide range of flowrate that is required means that the different modes of ventilation (whole-building, purge etc.) are likely to be provided via different devices such as trickle ventilators, opening windows and/or purpose provided ventilators. Such considerations will have considerable implications for the façade design and the control strategy, requiring a high degree of design integration. This is considered in detail in section 3.

As well as providing the required ventilation rates, the ventilators should be designed so as to minimise discomfort from draughts, especially in winter. In office-type buildings, this usually involves placing the inlets at high level, typically 1.7 m or more above floor level.

2.1.2   Control of summer overheating

Perhaps the single biggest issue that influences the technical viability of natural ventilation is summertime temperatures. The cooling potential of natural ventilation is limited by the prevailing climate and by occupant expectations of thermal comfort. As a rule of thumb, it is generally agreed that natural ventilation systems can meet total heat loads averaged over the day of around 30–40 W·m^{-2} (i.e. solar plus internal gains). If the effects of climate change become significant, then this rule of thumb may need to be revised downwards, although people's adaptation to a warmer climate may partly counterbalance the reduced cooling effect associated with warmer temperatures.

In most cases, achieving acceptable summer conditions requires three main features in the design and use of the building:

— good solar control to prevent excessive solar gains entering the occupied space

— modest levels of internal gains (people, small power loads and lighting loads)

— acceptance that during peak summer conditions, temperatures in the space will exceed 25 °C for some periods of time; air temperatures may be higher still, but in a well-designed building, such higher air temperatures will be offset by cooler mean radiant temperatures and enhanced air movement.

These issues are discussed in the following paragraphs.

2.1.2.1   Solar control

Compliance with Part L2 of the Building Regulations[5] requires that designers demonstrate that the building will not overheat due to excessive solar gains. The aim of this requirement is to prevent the tendency to retrofit mechanical cooling.

The compliance procedures for checking for solar overheating are developing with subsequent editions of Approved Document L2. In the 2002 edition, the compliance check was a rather coarse filter that checked the average solar gains over a design July day. This set a limit of 25 W·m^{-2} for the average solar load in a six metre deep perimeter zone, and assumed that internal gains were a modest 15 W·m^{-2} total, and that other mitigating factors such as effective thermal mass and night ventilation were present. The proposals for the 2005 edition, as published in the ODPM's consultation paper[11] are that detailed calculations will be required as part of the whole-building calculation approach required by the European Directive on the energy performance of buildings[12]. This new approach means that the benefits of thermal mass and night ventilation can be properly credited.

The forthcoming CIBSE TM37: *Design for improved solar control*[13] will provide guidance on the solar control performance that will be needed to limit overheating to a defined number of hours as a function of the key design parameters. Solar control can be achieved through measures such as:

— *Size and orientation of the glazed areas*: this will be influenced by the general organisation of the building on its site. Shading of the windows by surrounding buildings, and through self-shading from other parts of the same building can also contribute to reduced solar gains.

— *Tints, films and coatings in/on the glass*: recent developments in glass technology means that spectral-selective coatings are able to reduce solar gain without unduly reducing visible light transmittance.

— *Blinds*: internal, mid-pane or external.

— *Overhangs, side fins and brise-soleil*: the performance of these forms of solar control are orientation dependent and so different forms of control will be required on different façades. This will have implications for the aesthetics of the building.

The performance of these different systems (singly and in combination) can be quantified by the effective total solar energy transmittance, or effective g-value. This is defined as the solar gain through the window and its associated shading device during the period of potential overheating divided by the solar gain through an unshaded, unglazed aperture over the same period.

The design procedure suggested in TM37 is a two-stage process. The first is to determine the required effective g-value for the given building characteristics (window area, orientation, internal gains, thermal capacity and ventilation rates). The second stage is to select a solar control strategy that will achieve the required effective g-value.

In considering the glazing ratio and solar control features, an issue that must be recognised is that the climate has

become warmer over recent years (particularly in south-east England), and climate change predictions suggest that this trend will probably continue. Consequently, prudent design will take account of these possible future trends by either:

(*a*)   designing the building with some margin such that the building can cope with warmer conditions and still remain comfortable; the 2005 edition of CIBSE Guide A[9] contains data on future climate that can be used to assess how 'future-proof' is a given design

(*b*)   incorporating into the design means by which the building can be easily and cost-effectively reconfigured (e.g. by progressing to mixed-mode operation, see section 2.1.4) to cope with a warmer climate.

In addition to the possible impact of global warming, other effects can result in higher local temperatures that need to be considered when contemplating a naturally ventilated design. The most important is the heat island effect in large conurbations, which can be particularly significant in raising night-time temperatures. In turn, this will impact on the capacity to pre-cool the building using night ventilation. Guidance on the heat island effect is given in the CIBSE Guide A[9].

2.1.2.2   Internal gains

The internal gains in a space will also contribute to potential overheating. The three most important sources of gain are people, lights and small power loads (computers, printers, copying machines etc.). The level of internal gains is one of the inputs to the procedure described in TM37[13] but, as a general rule, if the solar load is about 25 $W{\cdot}m^{-2}$ and the average coincident internal gains over the day exceed about 15–20 $W{\cdot}m^{-2}$, then it will be difficult to ensure adequate comfort at all times, especially in SE England. The key aspects of this rule of thumb are the phrases 'coincident' and 'over the day'. The key is to try and minimise the coincidence of the gains, and to be more concerned with daily average gains than with peak gains. This suggests control of gains can be as important as specifying high efficiency equipment. This certainly applies to lighting but may also be relevant to business machinery, if equipment is specified that can switched to a low power 'standby' mode when not in immediate use. Further energy and comfort benefits can be obtained if the facilities management regime encourages all equipment to be switched off overnight. As discussed in a later paragraph, if occupancy periods are short, then higher levels of load can be accommodated.

In office buildings, occupant density is often quoted as one person per 10 m^2, but the British Council for Offices[14] advises that, in reality, very few buildings are that densely occupied and suggests that good practice is currently between 12 and 17 m^2 net internal floor area per person. It should also be recognised that occupant density will probably vary through the building, depending on the type of activity taking place in each space. Occupant density may also vary with time as the use of the building changes or working practices are modified. Occupant density may also vary over a much greater range (higher and lower) in other building types. For example, schools are often designed for natural ventilation, and yet have
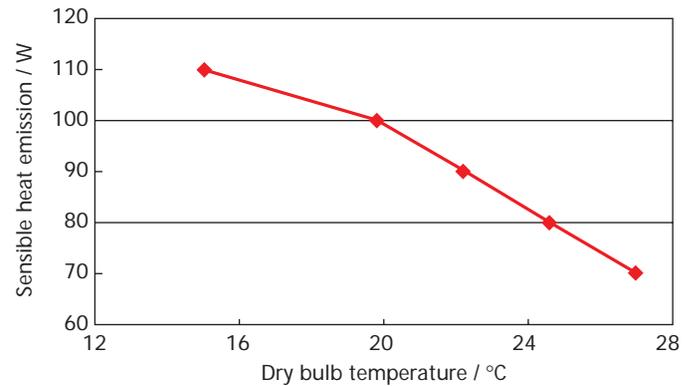

Figure 2.3 Relationship between temperature and heat emission

areas with a very high density of occupation. As well as assessing peak occupancy levels, the variation in occupancy through the day should also be considered, so that a realistic assessment of total gains through the day is made.

Heat emissions from occupants vary according to the level of activity. For sedentary activities such as office work, the average total heat emission from occupants is 130 W/person (average for typical mix of men and women)[6]. The division of this total heat emission into sensible and latent components varies as a function of air temperature as shown in Figure 2.3. This variation in heat emissions with temperature is important in the context of natural ventilation design since, as internal temperatures rise during hot weather, the magnitude of one of the sources of internal gains that contributes to the rise in temperature reduces significantly. This effect should be taken into account when estimating the risk of overheating, otherwise the likelihood of overheating will be overestimated.

Lighting is another important source of internal heat gain. The heat gain can be reduced by specifying efficient light sources and controlling the lights so that they are dimmed or switched off when natural light levels are adequate. Periods of overheating risk are most likely to occur during periods of strong sunshine, when daylight levels in perimeter spaces should be sufficient for most visual tasks. It is therefore important to provide effective lighting controls such that unnecessary lamps are switched off.

The Society of Light and Lighting's *Code for lighting*[15] gives guidance on the efficiency of a range of light sources. As a benchmark for design, installed lighting loads should be less than 3 $W{\cdot}m^{-2}$ per 100 lux (preferably nearer 2.5 and even lower in large open spaces). BRE Digest *Selecting lighting controls*[16] provides advice on the selection and specification of lighting controls.

One factor that needs to be considered is the interaction between any movable shading device (e.g. a blind) and the lighting. If blinds are closed to cut out direct solar gain, there is a danger that occupants will respond by switching on lights, thereby losing some of the benefit of the reduction in solar gains. It should also be appreciated that blinds are often used to control glare as much as solar gain. In such situations, it may be better to provide separate devices for the two functions, such as external shading for solar control, with occupant controlled internal blinds to control the glare. Ideally, the design of the solar control should not impact too significantly on the daylighting in the space. This can be done in a number of ways[17], such as:

— louvres, lightshelves or blinds that shade the main part of the window but direct daylight into the depth of the room

— selective coatings on the glass that restrict the transmission of radiation in non-visible parts of the spectrum.

The third main component of the internal load is that arising from machines such as computers, printers, vending machines etc. BCO guidance[14] suggests that when diversified over areas of 1000 m^2 or more, these loads seldom exceed 15 W·m^{-2}, although there may be local workstations peaking to 20–25 W·m^{-2}. These values may be exceeded significantly for specialist applications like dealer areas. Although these figures provide useful guidance, each space should be considered on its merits, both in terms of the anticipated activities for the space and in allowing flexibility for future change. To assist in such assessments, section 6 of CIBSE Guide A[6] gives guidance on heat gains from equipment.

Where there are particular items of equipment that have a significant heat output (e.g. a large copier or network printer), it may be sensible to provide such a machine with a local extract point. This will extract both heat and pollutants at source, thereby improving thermal comfort and indoor air quality.

As well as assessing the magnitude of the internal loads, it is also important to consider the duration of those loads. It may well be entirely practicable for a naturally ventilated building to cope with transient loads that are greater than the levels discussed above. In such situations, the designer has to think about the impact of the loads on both comfort and indoor air quality. In such situations, transient effects become much more significant. The thermal capacity of the structure can absorb significant swings in internal load, provided the structure has been pre-cooled before the loads build up.

2.1.2.3   Comfort expectations

A key criterion when assessing overheating is to define the thermal comfort conditions that are considered acceptable. Thermal comfort is a complex mix of physiology, psychology and culture. What is deemed acceptable will depend on activity and clothing level as well as temperatures, air speeds and humidity.
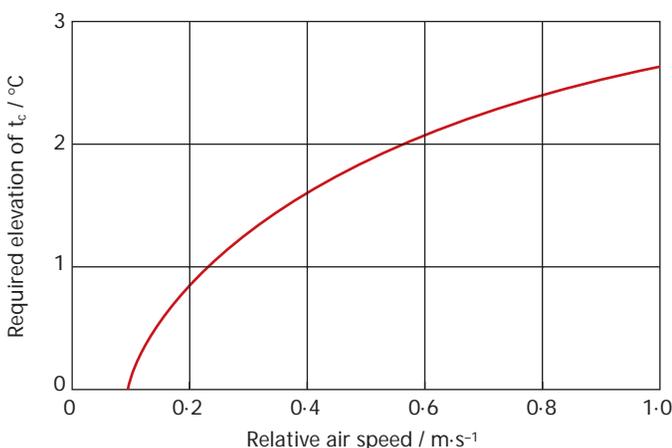
It is clear that a naturally ventilated building will deliver a more variable temperature than an air conditioned building, but that does not necessarily mean that occupants will be less comfortable. In summer, increased air movement from large openings can provide an enhanced perception of thermal comfort, but care has to be taken to avoid nuisance draughts, such as those that might blow papers off desks etc. Figure 2.4 shows how an air speed of about 0.25 m·s^{-1} is sufficient to give a cooling effect equivalent to a 1 K reduction in dry resultant temperature[6]. Such air speeds are only acceptable in the context of summer cooling, but this serves to illustrate an important mechanism by which natural ventilation can maintain thermal comfort in summer.

The cooling benefit can be further enhanced by employing a night ventilation strategy. This approach takes advantage of the lower external night-time temperature to pre-cool the building structure, and thereby lower the mean radiant temperature. By lowering the mean radiant temperature, comfort can be maintained even though air temperatures in the space might rise. By increasing thermal capacity, the amount of heat the structure can absorb per degree rise in mean radiant temperature increases, thereby increasing the ability of the space to maintain reasonable comfort conditions through the day.

The benefit of thermal mass is illustrated by Figure 2.5, which illustrates the influence of thermal mass and night ventilation on internal temperature[18]. Progressively moving from a lightweight construction with no night cooling to a thermally massive construction with high night-time ventilation reduces the peak internal temperature by nearly 5 K.

Thermal capacity is usually measured by the response factor[6], given by:

$$f_r = \frac{\Sigma\,(A\,Y) + C_v}{\Sigma\,(A\,U) + C_v} \tag{2.1}$$

where $\Sigma\,(A\,Y)$ is the sum of the products of all the surface areas bounding the space and their corresponding admittances (W·K^{-1}), $\Sigma\,(A\,U)$ is the sum of the products of the external surface areas and their corresponding thermal transmittances (W·K^{-1}) and C_v is the ventilation heat loss coefficient (W·K^{-1}).
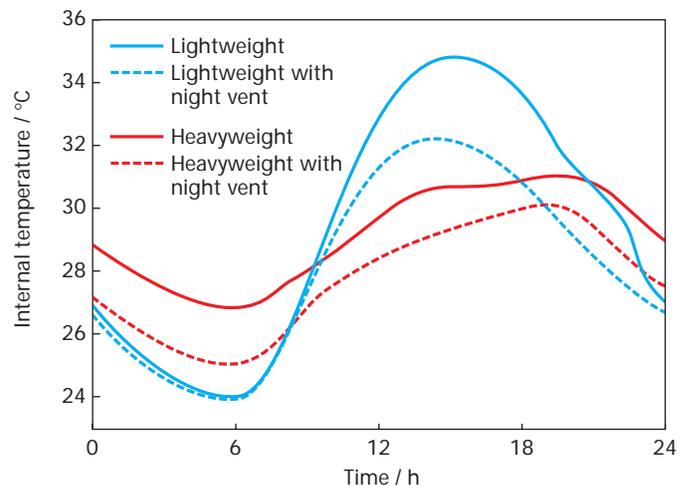

Figure 2.4 Effect of air speed on dry resultant temperature[6]

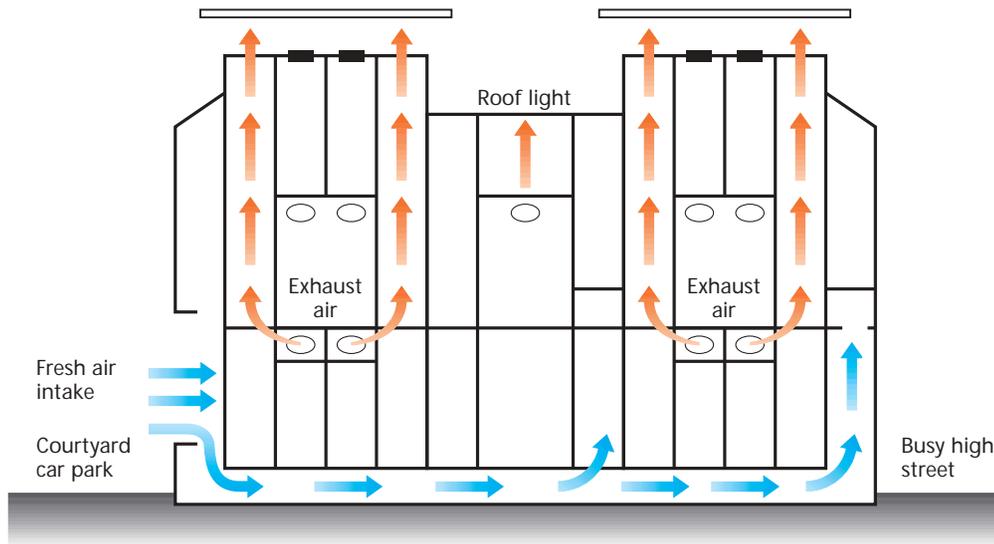**Figure 2.5** Effect of thermal mass and ventilation rate on peak indoor temperature[18]

Figure 2.6 Flow schematic: Canning Crescent Centre

Admittances and transmittances for a range of constructions are given in CIBSE Guide A[6,9]. Lightweight spaces are those with a response factor of around 2, medium-weight spaces have a response factor of about 4 and heavyweight spaces are those with a response factor of 6 or above.

Good natural ventilation design will also provide occupants with so-called adaptive opportunities to adjust their situation in response to changing conditions. This might involve:

— using blinds or other moveable shading to cut out direct solar radiation

— providing the opportunity to increase air movement by opening windows or the use of desk fans.

Coupled with less formal dress codes, these opportunities allow occupants to adjust their environment to suit their own preferences, allowing greater freedom of choice than is usually practical in an air conditioned environment. However, this does require careful design of the windows, their position and opening mechanisms, such that occupants can readily adapt their environment. This is discussed in detail in section 3.

Another important factor is that recent research has shown that in prolonged spells of warm weather, people's expectations for comfort change.

2.1.3 Acoustic performance

The presence of significant external noise sources is one of the main factors that inhibit the application of natural ventilation. There are two main solutions to this problem.

— *Place the ventilation inlets on the sides of the building away from the principal noise sources*: if the noise source is road traffic, this has the added benefit of locating the ventilation inlets away from the source of pollutants. The Canning Crescent Centre case study described in the output of the NatVent project[19] is a good example of this approach. The ventilation concept used is shown in Figure 2.6. However, it should be noted that there are subsidiary issues that need to be considered. Figure 2.6 shows the fresh air intake located in the vicinity of the courtyard carpark. Although this

will not be a significant noise source, it may be a source of pollution, particularly if there are idling vehicles near the intake such as cars queuing for the exit or delivery vehicles at a loading bay.

Integrate acoustic baffles into the ventilation opening: good acoustic performance in conjunction with natural ventilation is often a key design requirement for schools. BB93[20] provides guidance on ways to reconcile the needs of acoustic performance and natural ventilation. Figure 2.7 is a detail taken from that publication, illustrating how an acoustically protected ventilation opening might be integrated with the design of the window sill and the casing of the perimeter heating.

Another important acoustic issue is that of absorbing internally generated noise in spaces with large areas of hard surface, which are often associated with thermally massive buildings. The use of absorbent partitions or decorative hangings is one approach; another is to use carefully profiled ceilings that result in acoustic focus points below the absorbent floor level, such as used in the Inland Revenue building in Nottingham[21].
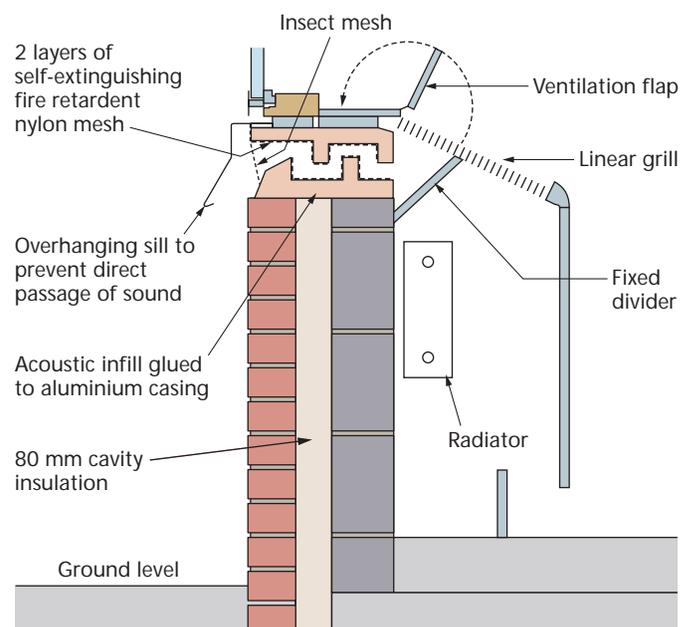

Figure 2.7 Ventilation opening with acoustic protection

2.1.4   Natural ventilation and mixed-mode

The above paragraphs give an overview of the factors that need to be considered when assessing whether natural ventilation is appropriate to the building under consideration. It should be recognised that not all parts of a building have to be treated in exactly the same way. Different strategies may be applied to different parts of a building, or at different times. This is the so-called 'mixed mode' approach, which is discussed in greater detail in CIBSE AM13[22]. The various approaches to mixed-mode are as follows:

(*a*)   *Contingency mixed-mode*: where flexibility of space is required, then it is important to 'design-in' the potential to upgrade the services so that additional cooling can be installed to meet tenant requirements or the changing climate. This provision will include space allowances for additional distribution systems incorporated into floor and/or ceiling voids. The cost of the additional flexibility will need to be set against the savings in initial and operating costs accruing from the avoidance of unnecessary air conditioning.

(*b*)   *Zoned mixed-mode*: recognises that different parts of any building will have different uses. Air conditioning is provided only to those parts of the building where there is a real need. In areas of lower heat gain, heating and natural ventilation only would be provided. Such an approach relies on the requirements of the individual spaces being reasonably constant over the life of the building. Such an approach can also create tensions, if one group of occupants feels that another group has been provided with what they believe is a better working environment.

(*c*)   *Changeover mixed-mode*: recognises that the cooling requirements of any space will vary from season to season. An example of changeover mixed-mode would be to use mechanical ventilation in extreme weather conditions (hot and cold), but rely on natural ventilation in milder weather. This reduces the problem of cold draughts in winter, and allows the use of mechanical night ventilation for pre-cooling in hot summer periods.

(*d*)   *Concurrent mixed-mode*: provides mechanical and natural ventilation simultaneously. The mechanical system is designed to provide the fresh air requirement, with additional ventilation by opening windows to provide summer cooling. The mechanical system can also provide night ventilation without the security problems that may be associated with opening windows. In very hot weather, energy wastage may occur if mechanical cooling is provided as part of a concurrent mixed mode system, since excess natural ventilation may impose an unnecessary fresh air load.

Figure 2.8 provides a flow chart that takes the user through a broad-brush decision tree to identify the most appropriate forms of ventilation.

2.1.5   Proceeding with the design

If on the basis of the above considerations it is concluded that natural ventilation is viable, either as the sole strategy or as a major component of a mixed mode approach, the next stage is to develop the design concept. Three basic steps need to be considered.

(*a*)   *To define the desired air flow pattern from the ventilation inlets through the occupied space to the exhaust*: this will be a function of the form and organisation of the building, which in turn will depend on its intended use and the details of the site. For example, if a heavily congested road bounds one side of the site, then it would be inadvisable to draw air into the building from that side because of the problems of pollution from vehicle exhausts.

(*b*)   *To identify the principal driving forces which will enable the desired flow pattern to be achieved*: certain strategies tend to be driven by wind pressures, others by temperature differences. In some cases, these natural forces will need to be supplemented with fans. Good design will ensure that the dominating driving forces are in sympathy with the intended flow distribution. This topic is the subject of the rest of section 2. Section 3 then gives details on the ventilation components that are available and how they should be integrated into a complete system.

(*c*)   *To size and locate the openings such that the required air flow rates can be delivered under all operating regimes*: this is in itself a three-stage process:

(1)   The flowrates have to be determined based on the air quality and thermal comfort requirements defined in the brief.

(2)   The openings have to be sized and located to deliver those flows under design conditions.

(3)   A control system must be specified to maintain the required flowrates under varying weather and occupancy conditions. Section 4 gives details of the calculation methods that can be used at this stage of design.

2.2   Selecting a natural ventilation concept

The first consideration is to plan the flow path through the building. This involves much more than drawing a series of arrows on a sectional view of the building. The form of the building has to be designed to facilitate the chosen strategy; the strategy then has to be engineered to ensure the air can flow along the chosen path at the required flowrates under the naturally available driving pressures. It should be appreciated that the building will need to operate in a number of different modes. In the heating season, driving forces will tend to be strong and the building will need to operate in 'minimum fresh air' mode. During mid-season, the building will move into a cooling mode in which outside air can be used to provide the cooling but driving forces will reduce. During peak summer conditions, outside air temperatures will exceed internal temperatures; this will reverse the direction of the stack-induced pressures but will also change the ventilation effect from cooling to heating. Therefore the building
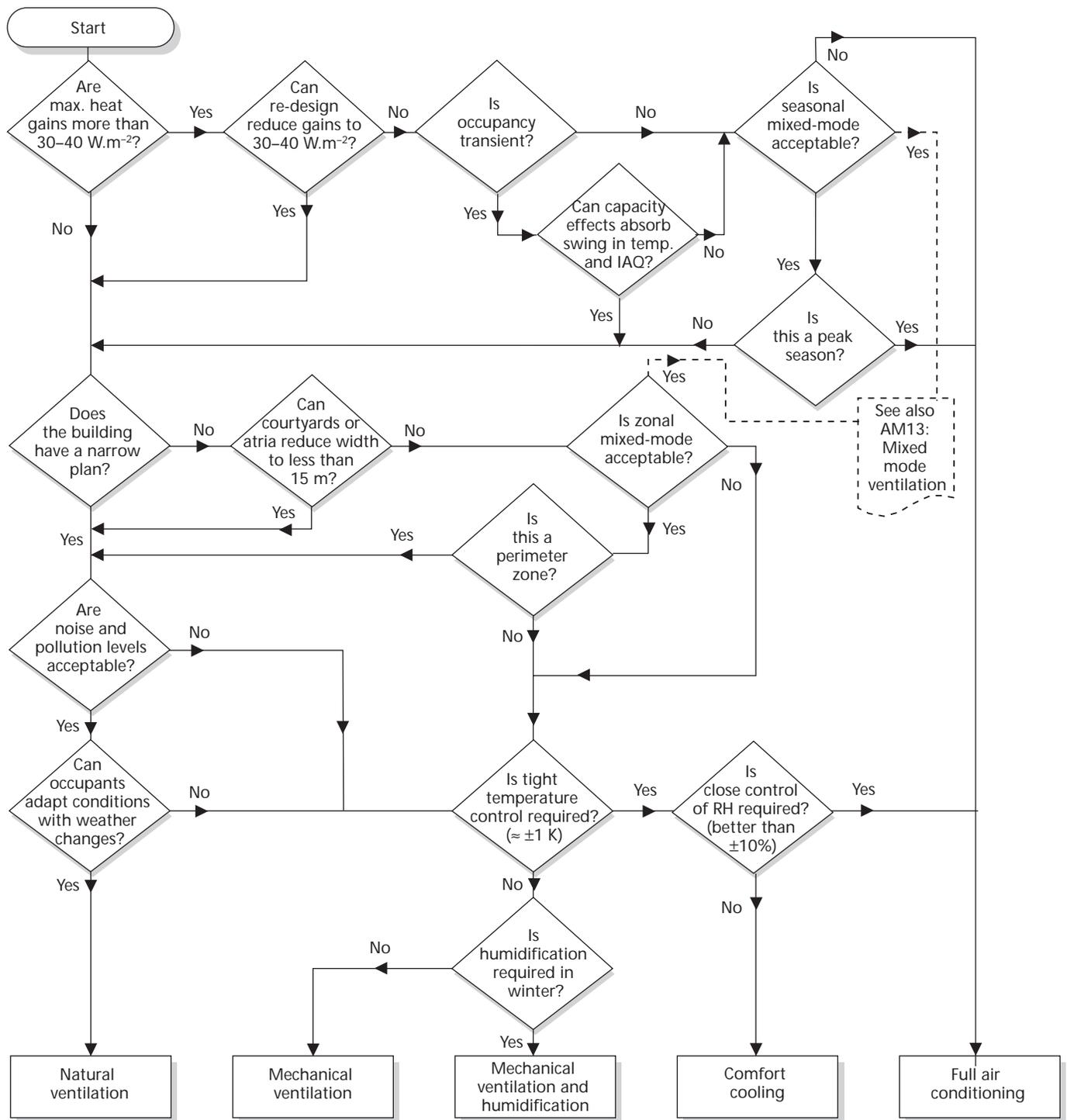
Figure 2.8 Selecting a ventilation strategy

may need to revert to operating in minimum fresh air mode.

Figure 2.9 illustrates the logic behind the development of the strategy for the Anglia Polytechnic building.

Figure 2.9 illustrates some key points, as follows:

— Cellular spaces will need to be ventilated in a different way to open spaces.

— Internal planning arrangements must allow the air to flow through the space towards the exhaust.

— In many buildings, the natural buoyancy of warmer air will involve an upward air movement so that substantial areas of exhaust opening must be provided at high level.

— Pollution sources (such as exhausts and flues must be positioned so as to minimise the likelihood of pollutants being re-ingested into the ventilation system)[23].

Fresh air must flow from outside, through the occupied areas and then to the exhaust point. The pattern of air flow must be considered for all operational regimes, winter and summer, as well as special operating modes such as cooling by night ventilation. This must include consideration of the impact of variations in weather conditions. For example, although one wind direction might predominate, the strategy will have to be sufficiently robust to work in all likely weather conditions. As well as the general pattern of air movement through the building, the needs of the occupants and the way in which these
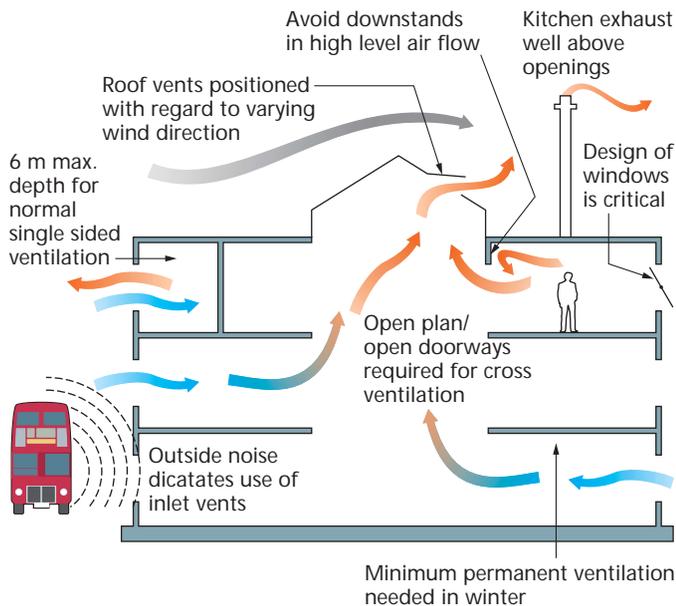
Figure 2.9 Ventilation schematic: Anglia Polytechnic

interact with the ventilation system must be considered. These issues are discussed in detail in section 3, but the practical issues which impact on the viability of any strategy must be kept in mind in the early stages of design. Trying to design around problems is rarely as successful as avoiding them in the first place.

The ventilation system is made up of a number of key components:

— *Ventilation inlet(s)*: where the fresh air is drawn into the ventilation system

— *Supply point(s)*: where that fresh air is delivered from the ventilation system into the occupied space. Usually, the inlet to the ventilation system is the same component as the supply point, (e.g. a trickle ventilator or an open window), but sometimes the ventilation inlet and room outlet may be separated by a distribution system such as a floor plenum. In such cases, access for cleaning will be an important issue.

— *Flow path*: through the occupied space to the exhaust point.

— *Exhaust path*: such as a stack.

— *Ventilation outlet*: where the air is exhausted outside the building.

Circulation areas such as stairwells or corridors can be used as distribution routes to deliver air to rooms that do not have direct access to the perimeter of the building. However, care must be taken to avoid these routes acting as 'short circuits' by providing a path of lower resistance from the supply to the exhaust, thereby preventing outside air entering the occupied zones.

Consideration must be given to the route the air will take through the building. For example, it may be beneficial to draw the air from one side of the building in order to:

— avoid noise and traffic fumes from a busy road

— draw cooler air from a shaded side of the building in order to maximise the cooling potential.

As the air flows through the space, it will pick up both heat and pollutants and therefore becomes less 'fresh'. Therefore, if the air is taken from one occupied zone to another, the downstream zone will have worse indoor air quality and probably poorer thermal comfort. It is therefore preferable either to extract from each zone direct to outside or via spaces with transient occupation such as circulation spaces or toilet areas.

In addition to the overall flow pattern, consideration must also be given to the detail. The ventilation air has to be introduced into the space in such a way as to avoid stagnant areas which may lead to local discomfort due to poor indoor air quality or poor thermal comfort. This means that the openings must be well distributed.

As discussed in section 2.1.1, the range of ventilation rates that will be required may vary over an order of magnitude. In order to provide effective control over such a wide range, different ventilation openings may be required for the different ventilation modes.

2.3   Driving forces for natural ventilation

The magnitude and pattern of natural air movement through a building depends on the strength and direction of the natural driving forces and the resistance of the flow path. Good design involves the appropriate application of fundamental principles to the general strategies described in the following sections.

It is important to appreciate that the discussions that follow describe steady-state ventilation scenarios. The two important driving forces of wind and buoyancy (caused by heat gains in the space) are always varying. As conditions change, the ventilation rate will also change, and the flow direction might even reverse under extreme conditions. These steady-state 'snapshots' are therefore an idealisation of reality. The flow pattern needs to be thought through for each of the main operating modes (see discussion at the beginning of section 2.2). The most critical operating mode in terms of sizing vents is the condition where the ventilation is providing summer cooling with a small inside–outside temperature difference. This mode will require the largest vent sizes, with the control system throttling back on this condition at the other operating conditions. The size of the vents will be dictated by the required flowrate and the available driving pressures caused by wind and buoyancy.

In order to understand the relative importance of wind and buoyancy forces, Figure 2.10 shows the pressure difference driving the flow as a function of the driving force (temperature difference or wind speed). In Figure 2.10(a), two height differences are shown, 3.5 and 10.5 m, typical of the distance between the top floor of a building and a stack outlet and the whole of a 3-storey building and the same stack outlet. The lines on the graph show the stack pressures corresponding to the inside–outside temperature difference given along the *x*-axis. In a similar way, in Figure 2.10(b) two lines are shown representing wind driven pressure difference for a typical range of pressure coefficient difference between inlet and outlet (0.1 to 0.5). The shaded boxes show the typical conditions which exist at the summer design condition, namely an
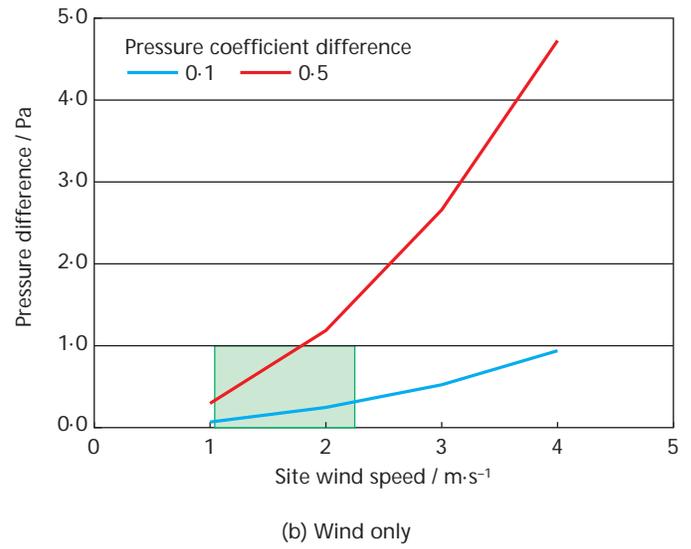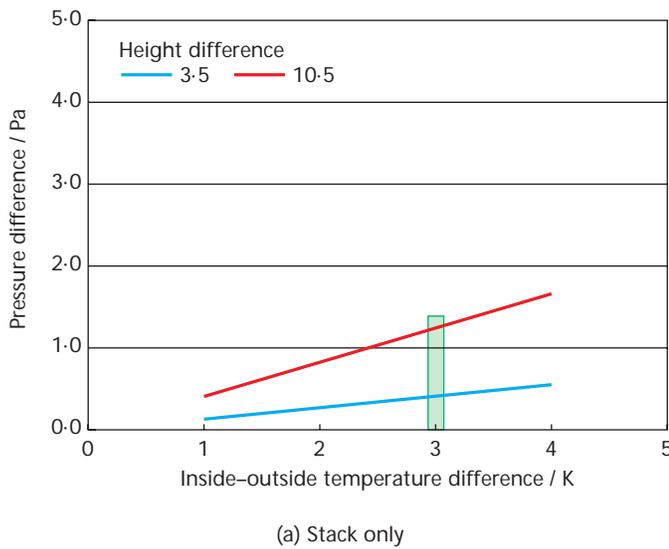
(a) Stack only

(b) Wind only

Figure 2.10 Relative driving pressures

inside–outside temperature difference of about 3 K and a wind speed of between 1 and 2.2 m·s^{-1} (depending on terrain conditions).

Figures 2.10(a) and 2.10(b) illustrate that at the summer design condition, the stack and wind driving forces are likely to be comparable, unless the design can deliver very large differences in wind pressure coefficient between inlet and outlet. It is difficult to achieve a high difference in pressure coefficient for all wind angles, and because wind direction is inherently variable, a design that relies on a large difference in pressure coefficient is unlikely to be very robust. For this reason, design practice is often to size the openings based on stack effects alone, and to engineer the design so that any wind effect will enhance the driving forces (e.g. through careful design of the stack outlet).

The ventilation through the building is driven by these differences in pressure. The ventilation rate is determined by the pressure difference acting across a ventilation path and the resistance of that path. Section 4 gives the detailed mathematical treatment of these effects, but the present section concentrates on explaining the physical processes themselves. The section then summarises how these processes can be harnessed to deliver a variety of natural ventilation concepts.

2.3.1 Density differences ('stack effect')

Warm air is less dense than colder air. Therefore, if two columns of air at different densities are connected, the cooler, denser air will fall and displace the warmer, lighter air upwards. Consider a very simplified building in the form of a box (see Figure 2.11). At most times of the year, the air inside the building is warmer than the external air as a result of the building heating system and/or the effects of internal gains. Hydrostatics require that the pressure at a point decreases with height, the rate of decrease being proportional to the density of the fluid. This is shown in the Figure 2.11 by the two pressure gradients. Because the outside air is colder, it is denser, and therefore the pressure decreases with height more rapidly outside the building (the blue line) than inside (the red line).

Because the internal and external pressures change with height, there will exist pressure differences across the

separating walls. If holes are now placed within the separating wall, an air exchange will be set up in proportion to the pressure difference acting across it. In order to visualise the effects, the pressure gradients acting inside and outside can be placed against a scale such that the point where the pressures are equal occurs at the mid point of the wall, as shown in Figure 2.12. When this is done, the horizontal distance between the lines representing the two gradients is a measure of the pressure difference between the inside and outside of the building. In order to simplify the subsequent diagrams, these only show that part of the building enclosed by the green line.

Three physical relationships control the flows that are set up. These are:

— *Conservation of mass*: the airflow into the building must be balanced by the exhaust flows.

— *Hydrostatic pressures*: the pressure gradient is proportional to the air density. If the air is at a uniform temperature, the density is constant and the gradient is a straight line (this is the case shown in the diagrams). If temperature varies with height, then the slope of the pressure gradient will also vary with height and become a curved line.
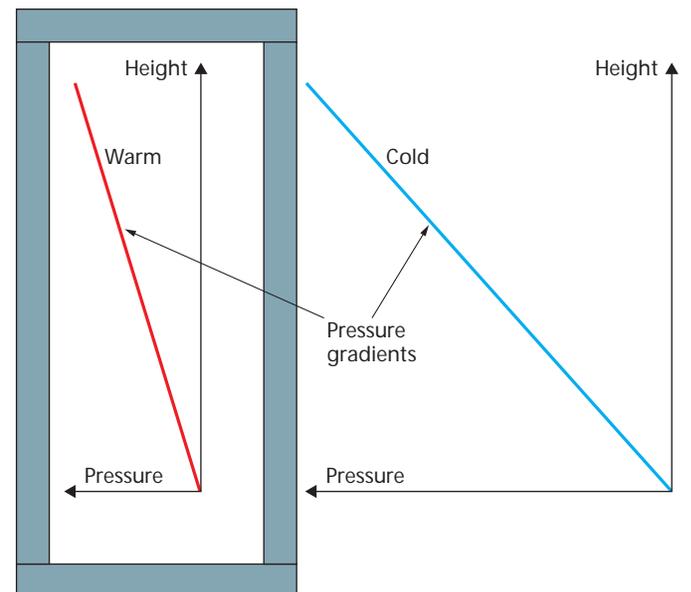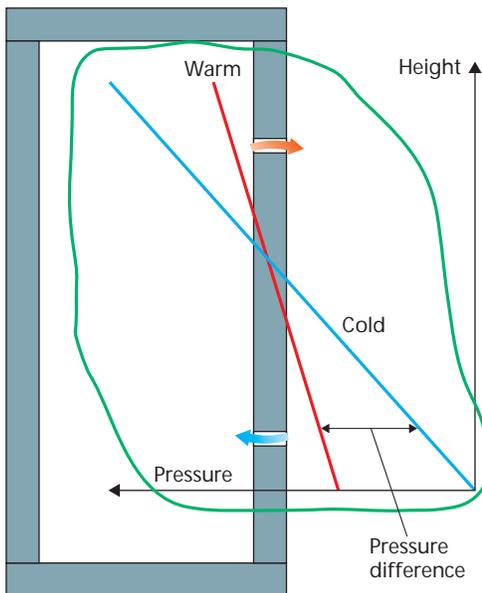

Figure 2.11 Schematic of pressure gradients

Figure 2.12 Representation of airflows

Figure 2.13 Impact of size of openings on neutral pressure level; (a) openings of equal size, (b) openings unequal

—   *The flow equation*: flow through cracks and openings depends on the area, the discharge coefficient and the pressure difference; the bigger the hole and/or the bigger the differential pressure, the greater the flow.

These relationships are developed in mathematical terms in section 4.

Consider the two cases shown diagrammatically in Figure 2.13. In Figure 2.13(a), the size of the two holes are the same; in (b), the size of the lower hole is twice that of the upper. In order to satisfy the law of the conservation of mass, the airflow that develops will be such as to equalise the flow through the two openings. Because in (a) the two holes are the same size, the pressure drop across each opening must be the same in magnitude, but acting in opposite directions. Hence the relative position of the two gradients adjust themselves until the pressure drops across the two openings are the same. The height at which the two gradients intersect is the neutral pressure level (NPL), which, in (a) is midway between the two openings.

In (b), because the lower hole is bigger, its resistance to flow is lower than in the upper opening. Therefore, in order to fulfil the law of mass conservation, the pressure drop across the lower opening must decrease, and that across the upper will increase until the flows equalise once more. The neutral pressure level is still defined by the point at which the two pressure gradients intersect, but now it can be seen that this level occurs at a point much lower down the wall.

In all cases, below the NPL air will flow from the cold side to the warm and, above the NPL, from the warm to the cold. For most of the year, the temperature outside the building will be cooler than inside, and so the air will be rising up through the building. However, in very warm weather, it may be that the outside temperature exceeds the internal, in which case the flow will reverse. If this is undesirable, the designer can make unoccupied parts of the building deliberately warmer than outside so as to maintain a constant direction of flow. This can be achieved through solar chimneys, or by trapping solar gain at the top of an atrium (see 2.4.3.2).
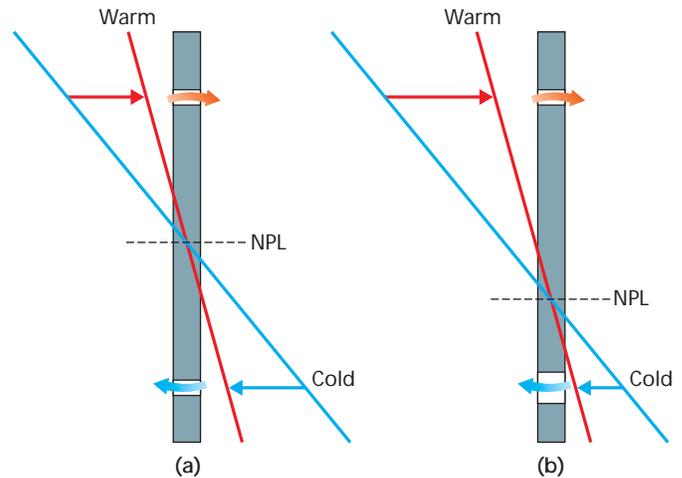
It is also important to note how changing the size of an opening influences the position of the NPL. This is particularly relevant in the context of real natural ventilation design, where the building has several storeys. Figure 2.14 shows a three storey building, with outside air being drawn in at each level and being exhausted via a high level outlet above the top occupied floor. In this example, it is assumed that the same ventilation rate is required at each occupied level.

In this context, the sum of all the inflows has to balance the single high-level outflow. To achieve the required flow distribution, the NPL has to be forced above the height of the highest occupied floor, otherwise warm air from lower floors will exhaust through the top occupied floor, resulting in poor thermal comfort on the top floor.

As will be seen from Figure 2.14, the driving pressure at the ground floor level is much greater than that at the second, which is correspondingly greater than that at the third. If equal flowrates are to be obtained, this must be achieved by varying the opening size at each level. If the required opening size on the third floor level was thought to be too large, the available pressure drop could be made greater by forcing the NPL still higher. The problem is that this will reduce the available pressure drop at the exhaust vent, requiring a bigger vent size. The alternative would be to raise the height of the stack, but this would have cost (and possibly planning) implications.

The fact that the ventilation openings are smaller at lower levels has some security benefits, particularly where a night ventilation strategy is employed.

Another important point is that, since the magnitude and balance of the air flows is very dependent on the size and location of the openings, it is essential that there are no unintentional flow paths through the building envelope since these could undermine the design intent. This highlights the importance of achieving a good standard of airtightness in the envelope[24]. Problems have been experienced in a building with a poorly sealed atrium roof and a poorly designed entrance lobby. In this situation, there are much larger than expected openings at both high and low levels, resulting in very strong draughts at the entrance and through the atrium.
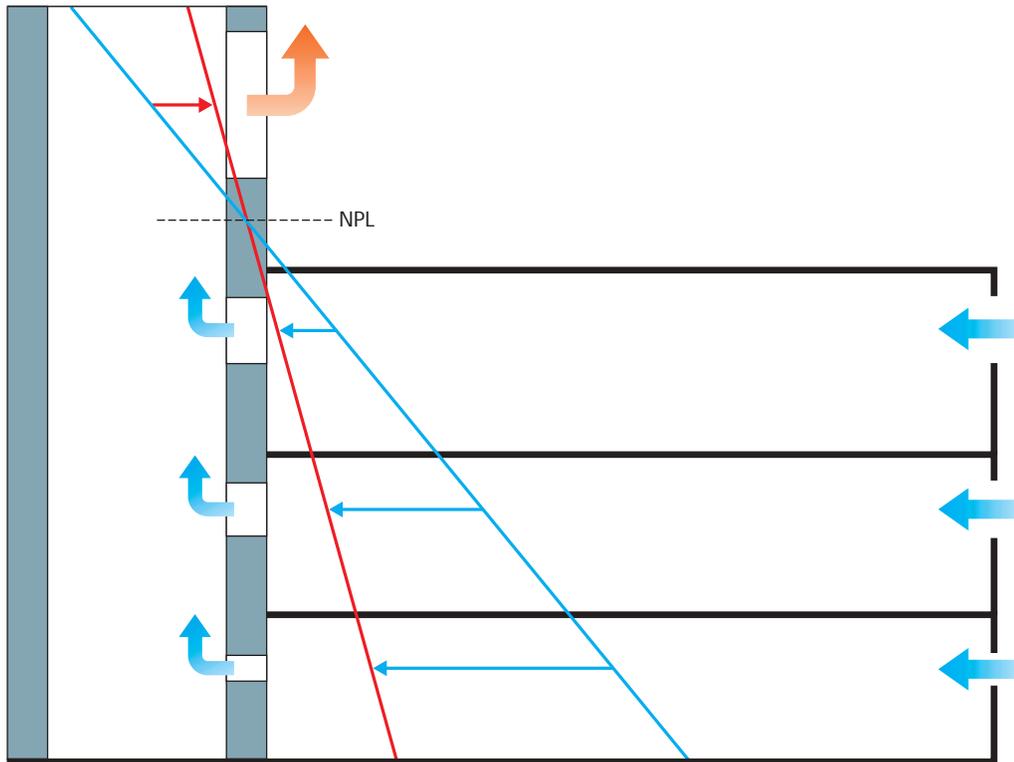
Figure 2.14 Application of stack effect to a realistic building design

NPL

2.3.1.1   Local stack effects

Stack effects do not occur just over the whole height of the building. Stack pressures will be exerted over any vertically spaced openings that are inter-connected. For example, in a large window opening, air will tend to flow in at the bottom and out at the top. This creates an air exchange mechanism in the room even if it is isolated from the rest of the building by a well-sealed door. In a building designed to promote stack induced flows, these local stack effects will be superimposed on the overall pattern of air movement.

2.3.2   Wind

Wind driven ventilation is caused by similar physical relationships as stack driven ventilation, except that the pressures are the result of varying surface pressures acting across the building envelope rather than differences in hydrostatic pressure. As the wind approaches the façade of the building, the air is slowed and the pressure rises. As it flows around the building, the air accelerates over the roof and sides, resulting in a lowering of the local surface pressure. At the downstream face, the flow separates from the roof and sides resulting in low pressure recirculation zone. This is shown diagrammatically in Figure 2.15.

The distribution of pressure over the surface of the building depends on the following:

—   *Wind speed and its direction relative to the building*: the local wind speed is affected by the type of terrain surrounding the building (e.g. open country or city centre). The more congested the terrain, the slower will be the local wind speed relative to the quoted meteorological wind speed.

—   *Shape of the building*: this provides the opportunity for the architectural form and detailing to enhance the potential for wind driven ventilation.

Air will flow through the building from areas of high surface pressure to areas of low pressure. In very general terms, building surfaces facing into the wind will experience positive pressures; leeward surfaces and those at right angles to the wind direction will experience suction. As shown in Figure 2.15, wind velocity increases with height. The velocity pressures of the wind increase as the square of wind speed and so the wind pressures on high-rise buildings can be very large during periods of high wind speed. The surface pressure acting on the building is related to the velocity pressure of the wind by the wind pressure coefficient, which will vary from façade to façade, and will also vary across a façade.

Because the wind develops a pressure difference across the width of the building, the normal approach to wind driven ventilation is to design flow paths that are largely horizontal, with air entering and leaving the building at the same vertical level. However, by careful design of the top of a stack, wind forces can be used to induce vertical flows through the building (see section 2.4.2).
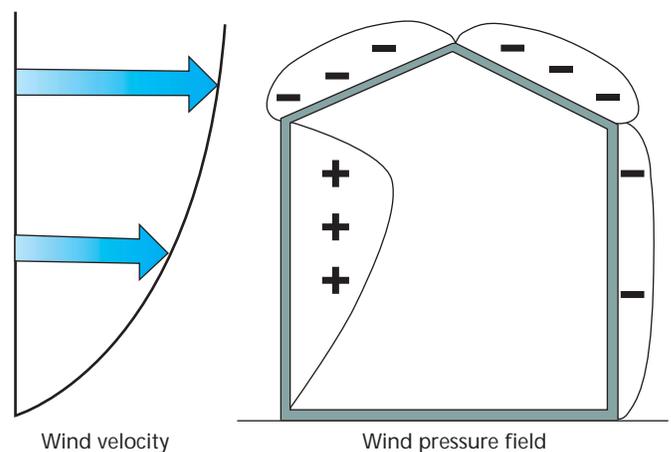

Wind velocity   Wind pressure field

Figure 2.15 Wind pressures acting on the building

Careful orientation of the building relative to the topography of the site and the prevailing wind direction can maximise the potential of wind driven ventilation, although the variability of wind direction must always be considered.

Site conditions can be enhanced by landscaping, such as the planting of trees to act as shelter belts. If there are multiple buildings to be developed on the site, then the relative positions of the buildings can enhance the flow pattern of the wind. Consideration must be given to the effects of high wind speeds in winter. In order to understand these complex effects, it may be necessary to undertake wind tunnel tests (see section 4.2.7).

When the wind acts on a large opening, especially if the angle of attack is non-orthogonal, then different wind pressures will act on different areas of the opening. This is one mechanism whereby ventilation can be driven in spaces that only have a single opening. The other mechanisms are wind turbulence (section 2.3.2.1) and buoyancy (section 2.3.1.1).

2.3.2.1   Wind turbulence

Wind is never steady in either magnitude or direction. Consequently, the wind exerts a continuously varying pressure field over the building. In most situations, the time-averaged pressure is sufficient to determine the average ventilation rate, but there are situations where the unsteadiness or turbulence of the wind can be an important factor in determining the ventilation rate. The main situation is where the space is being ventilated through a single opening.

In such situations, a steady pressure difference cannot develop across the space because there is not a separate inlet and outlet. Although a steady pressure may be generated at the face of the opening, all that this does is to raise the pressure in the enclosed space to that steady pressure. As has been intimated, the pressure will never be steady, and so the opening will experience a rapidly fluctuating pressure, alternately higher and lower than the mean pressure in the enclosed space. This means that the pressure difference across the opening will be continuously reversing direction, sometimes forcing air into the space sometimes extracting air from it, hence creating an
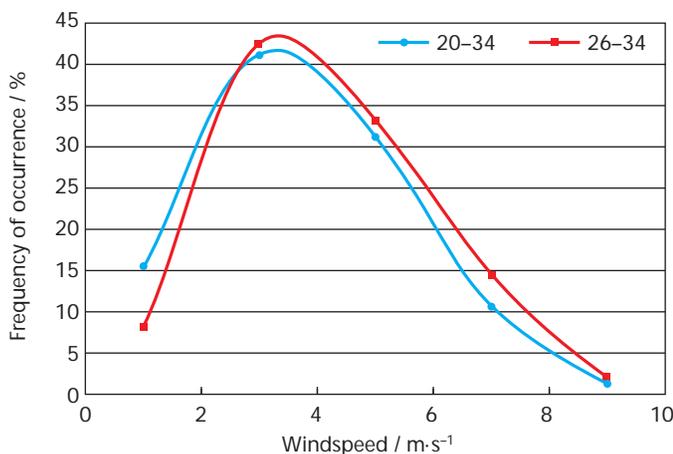
air exchange mechanism. Although the mechanism can be explained in physical terms, and anecdotal evidence suggests it can provide adequate ventilation for rooms of shallow depth, information on the magnitude of such effects is not available at present.

2.3.3   Combined wind and stack effects

The above discussions of wind and stack effects have presented an idealised explanation of the mechanisms that drive natural ventilation. In reality, these effects never act in isolation. Analysis of the data given in CIBSE Guide A[6] Tables 2.18 and 2.19 shows that the wind speed coincident with the temperature that is not exceeded for 99.6% of the time is in excess of 3.5 m·s^{-1} for all UK locations. Figure 2.16, based on data in CIBSE Guide J[25], illustrates the frequency of wind speeds for two temperature ranges: 20–34 °C and 26–34 °C. It demonstrates that most of the time there will be significant wind speeds to help drive natural ventilation. It should be noted that these are meteorological wind speeds, and that the effects of the terrain type will be to reduce the apparent wind speed at the building location, especially in urban areas and city centres.

The important point to note is that the natural ventilation rate that will occur will be the result of the combined effects of wind and stack. Therefore, although the design may be concentrating on utilising one mechanism, the effects of the other must not be ignored. For example, in Figure 2.14 if the wind were blowing from the left, the openings would all be on the leeward side, and this would result in a negative wind pressure on the outside of each opening. The pressures acting on each opening can be combined (taking account of their direction).

This is shown diagrammatically in Figure 2.17, in which the outline of the building has been removed for simplicity. Figure 2.17(a) shows the two stack pressure gradients, with the length of the horizontal arrows representing the magnitude of the resulting pressure difference across each opening. Figure 2.17(b) shows the variation in wind surface pressure with height. Note that this pressure profile is relative to an arbitrary datum pressure. In order to calculate the pressure drop across the opening, this profile must be related to the internal pressure in the building. For the required flow pattern to occur in practice (inflow at the lower three openings and exhaust via the top), the internal pressure would adjust itself so that the variation in pressure difference with height is as shown in Figure 2.17(c), where the pressure difference changes sign somewhere between the second floor vent and the outlet. This adjustment of the internal pressure is achieved by judicious sizing of the ventilation openings. The internal pressure that achieves the required condition is shown on the wind pressure profile. It can be seen that although the external surface pressure is negative at all openings, the internal pressure is even lower for the three inlets, resulting in the wind and stack effects reinforcing each other at these levels, as indicated by the length and direction of the green arrow between the internal pressure line and the wind pressure profile. The opposite is true at the outlet.

Figure 2.16 Frequency of summertime windspeeds in the UK

Clearly, if the distribution of wind pressure over the surface of the building were different to that assumed in the figure, a different flow pattern might result. It should be stressed that the overall flowrates cannot be determined by calculating the flow due to each mechanism separately, and then adding the results together. This is because the flow through a typical ventilation opening is non-linear, and so it is the pressures that must be added and then the combined pressures used in the flow equation. The mathematical treatment of this subject is dealt with in detail in section 4.

2.4   Natural ventilation strategies

In the following sections, the basic forms of ventilation strategy are reviewed and related to the form and layout of the building for which they are best suited. The rules of thumb for estimating the effectiveness of natural ventilation given in the following paragraphs are based on information provided in BRE Digest 399[26]. The relevant design calculations contained in section 4 are also cross-referenced.

2.4.1   Single sided ventilation

Single sided ventilation relies on opening(s) on one side only of the ventilated enclosure. It is closely approximated in many cellular buildings with opening windows on one side and closed internal doors on the other side.
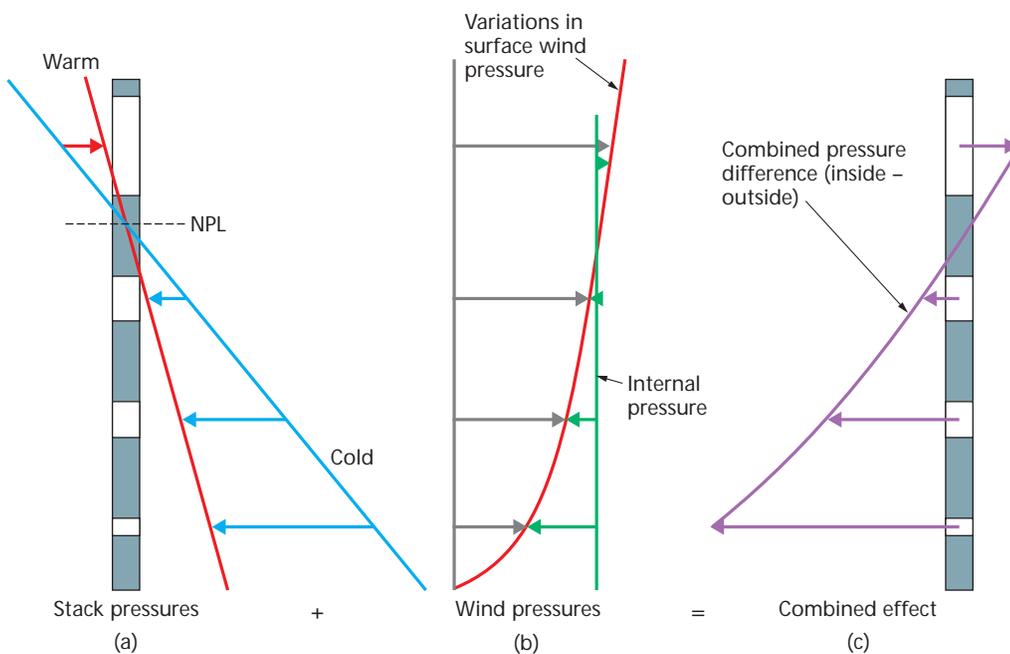
2.4.1.1   Single opening

With a single ventilation opening in the room, see Figure 2.18, then in summer the main driving force for natural ventilation is wind turbulence. Relative to the other strategies, lower ventilation rates are generated and the ventilating air penetrates a smaller distance into the space. As a rule of thumb, the limiting depth for effective ventilation is about twice the floor-to-ceiling height. It is also possible to get buoyancy driven exchanges through a single opening provided the opening is reasonably large in the vertical dimension. See cases 2 and 3 in section 4.

2.4.1.2   Double opening

Where multiple ventilation openings are provided at different heights within the façade, see Figure 2.19, then the ventilation rate can be enhanced due to the stack effect. See case 1 in section 4.

The stack induced flows increase with the vertical separation of the openings and with the inside to outside temperature difference. As well as enhancing the ventilation rate, the double opening increases the depth of penetration of the fresh air into the space. As a rule of thumb, the limiting depth for effective ventilation is about 2.5 times the floor-to-ceiling height

To maximise the height over which the stack pressures act, it may be necessary to separate the ventilation openings
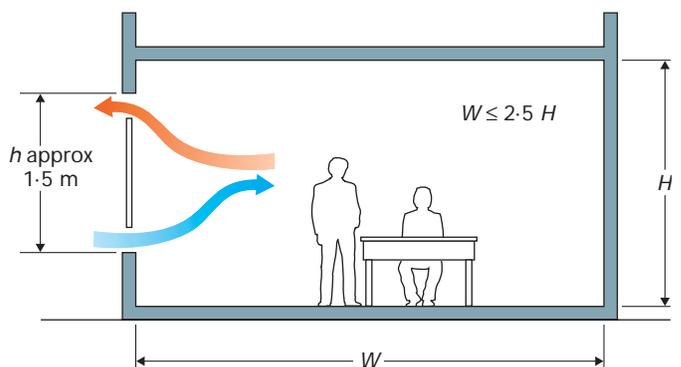

Figure 2.17 Combining wind and stack pressures
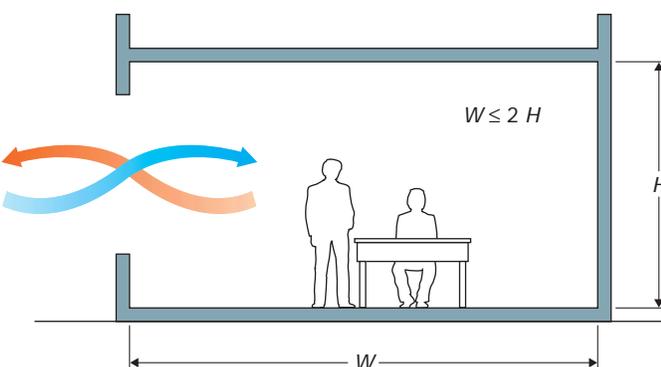
Figure 2.18 Single sided ventilation, single opening

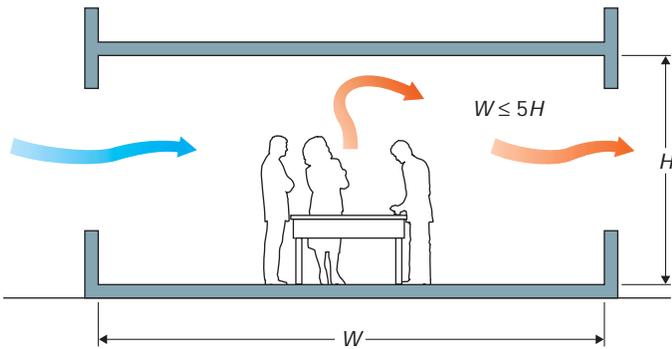**Figure 2.19** Single sided ventilation, double opening

Figure 2.20 Cross ventilation

from the window itself. Care needs to be taken over the position of any low level inlet, because it may create low-level draughts in cold weather. One solution is to place the low level inlet behind the radiator. However, in mid-season it may be that the internal and solar gains are sufficient to maintain satisfactory internal temperatures and so the radiator may have switched off, in which case there may still be a draught risk. Another potential problem is that if wind effects are significant, an opening behind a radiator may act as an outlet as well as an inlet. If it is acting as an outlet, then some of the heat from the radiator will be lost to outside without warming the zone.

2.4.2   Cross ventilation

Cross ventilation occurs where there are ventilation openings on both sides of the space, see Figure 2.20. Air flows in one side of the building and out the other side through, for example, a window or door. Cross ventilation is usually wind driven, but can be driven by density differences in an attached vertical chimney. As the air moves across the zone, there will be an increase in temperature and a reduction in air quality as the air picks up heat and pollutants from the occupied space. Consequently there is a limit on the depth of space that can be effectively cross-ventilated. The rule of thumb for the maximum distance between the two facades is five times the floor-to-ceiling height. This implies a narrow plan depth for the building. This is usually achieved with a linear built form, although a similar effect can be achieved by 'wrapping' the building around an open courtyard. The narrow plan depth associated with this approach has the added benefit of enhancing the potential for natural lighting.

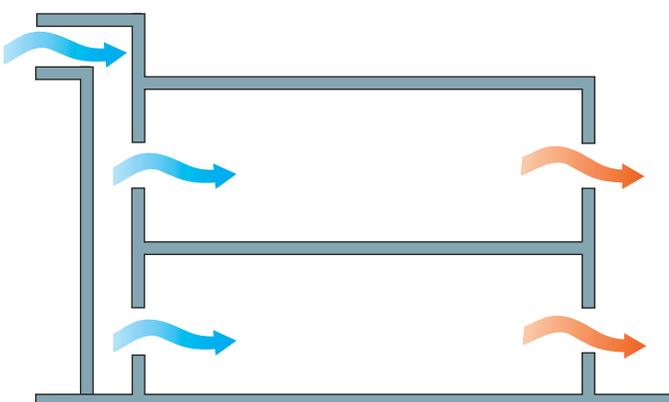The main design challenge with such an approach is to organise the form of the building such that there is a significant difference in wind pressure coefficient between the inlet and outlet openings. This will be more difficult to achieve for the courtyard approach, because the courtyard and the leeward side of the building will be at similar pressures.

The second issue that needs careful consideration is the resistance to airflow. Insufficient flow may be generated, particularly in summer conditions, if openings on one side of the building are closed, or if internal partitions (particularly full height ones) restrict the flow of air across the space. In such situations, the ventilation mechanism will revert to single sided.

The normal approach to cross ventilation is via opening windows (see case 4 in section 4), but other approaches have been used with success. One example of this approach is the 'wind-scoop', see Figure 2.21, which captures the wind at high level where the dynamic pressure of the wind is higher, thereby creating additional pressure to drive the air through the building to the exhaust on the leeward side. When designing a wind scoop, the effect of stack pressures must be considered, since these may act in opposition to the intended flow.
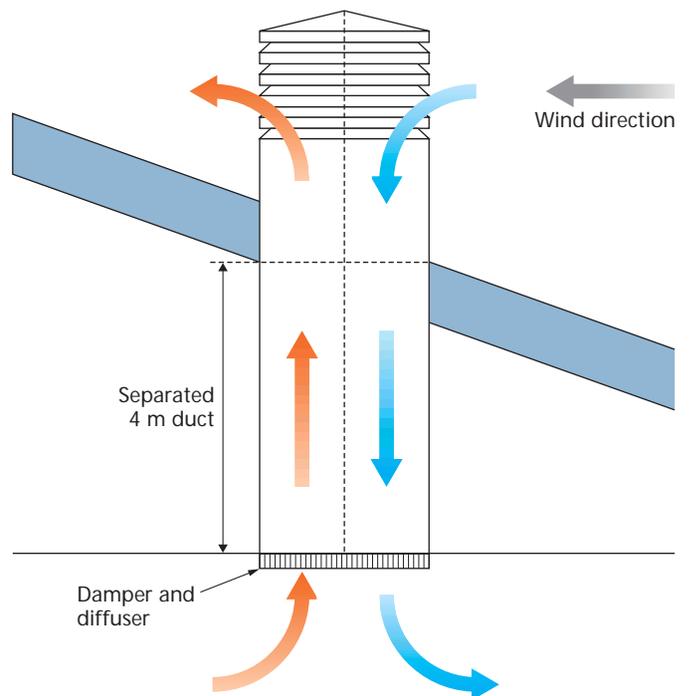

Figure 2.22 Roof-mounted ventilator

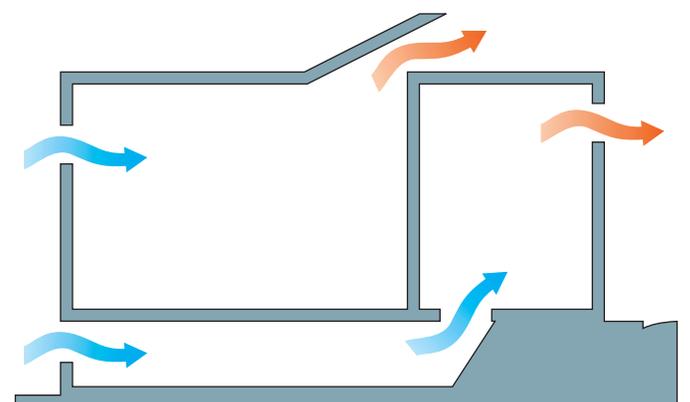**Figure 2.21** Wind scoop

Figure 2.23 Underfloor ventilator

The success of the strategy is enhanced by a dominant prevailing wind direction, (e.g. a coastal site). Where wind direction does vary frequently, then it would be necessary to have multiple inlets, with automatic control closing the leeward and opening the windward vents. Because of the increasing wind speed with height, the wind pressure will be greatest at the top of the structure, thereby generating a positive pressure gradient through the whole building.

A modern variant of the wind scoop is the roof-mounted ventilator[27], see Figure 2.22. This uses the pressure difference across a segmented ventilation device to drive air down through the segment facing the wind and into the space. The suction created by the negative pressure on the leeward segment then draws the air back out of the space. Flow rate can be controlled using a damper, with air distribution being achieved via a diffuser module*.

In order to improve air distribution into deeper spaces, it is possible to use ducted or underfloor ventilation pathways, see Figure 2.23. This approach provides fresh air directly to a second bank of rooms. It also provides a method of ventilating a building from only one side if a pollution source (e.g. a busy road) prohibits opening windows on the other facade. Because of the low driving pressures with natural ventilation, it is important to design the supply duct for very low pressure drops.

2.4.3 Stack ventilation

Stack ventilation is driven by density differences. The approach draws air across the ventilated space and then exhausts the air through a vertical flow path. This means that occupied zones are cross-ventilated, in that air enters one side of the space and exits via the opposite side. The same rule of thumb for effective ventilation therefore applies as for wind driven cross ventilation, i.e. the limit is about five times the floor-to-ceiling height. The air may flow across the whole width of the building and exhaust via a chimney, or it may flow from the edges to the middle to be exhausted via a central chimney or atrium. A detailed review of stack driven ventilation is given by Riain and Kolokotroni[28], and the required design calculations are described in cases 5 to 8 in section 4.

In order to achieve the required flow distribution without excessively large outlet ventilator sizes, it is usually the case that the stack outlet needs to be at a height at least half of one storey above the ceiling level of the top floor. The calculation methods given in examples 5 to 8 in section 4 explore this issue. Designing the stack outlet so that it is in a wind induced negative pressure region will enhance the effectiveness of the stack. This requires careful design of the position and form of the stack outlet.

2.4.3.1 Chimney ventilation

Chimneys provide a means of generating stack driven ventilation. The essential requirement is for the air in the chimney to be warmer than the ambient air. If the chimney has a large surface area exposed to the prevailing weather, this has to be well insulated in order to maintain the required temperature differential.

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* The extent to which good air distribution can be achieved will be limited by the available driving pressure, which will rarely be as great as the 10–30 Pa that is dissipated across the diffusers used in mechanical ventilation systems.

Figure 2.24 Solar chimneys at BRE's Environmental Building

It is possible to enhance the temperature (and hence density) differences by using solar heat gains to increase the air temperature in the chimney. In this mode, glazed elements are included in the chimney structure. The glazing allows solar radiation to be captured within the chimney by absorbing surfaces that then release heat to the air, thereby promoting buoyancy. The 'pull' of the stack is enhanced by having as high a temperature as possible over as much of the length of the stack as possible. Therefore having low level glazed elements in the stack will facilitate a temperature lift along the full length of the chimney, always provided the low level glazing is not shaded by trees or other buildings.

Care has to be taken to ensure that there is a net heat gain into the chimney during cooler weather (i.e. the solar gain must be greater than the conduction loss). If this balance is not achieved, the buoyancy effects will be reduced and the chimney will be less effective. In cold weather, the conduction heat loss will result in low surface temperature for the glass. This may be sufficient to generate down draughts that may inhibit the general upward flow through the chimney.

An advantage of the solar chimney is that it is likely to be placed on the sunny side of the building in order to capture the solar radiation. Consequently, the ventilation air will be drawn from the opposite (shaded) side, resulting in cooler air being drawn into the building.

Another important part of the design of any type of chimney ventilation is the detail of the outlet, which should be located in a negative wind pressure zone. This negative pressure zone can be created by careful design of the roof profile and/or the chimney outlet. If the outlet is not properly designed, positive wind pressures may act on the chimney, making it act as a wind scoop (see Figure 2.21) thereby disrupting the flow strategy.

As a means of providing adequate ventilation on very hot and still days, consideration might be given to installing extract fans in the chimney to pull air through the building. This should be arranged in such a way that the fans do not provide a significant resistance to flow when the chimney is operating in natural draught mode.
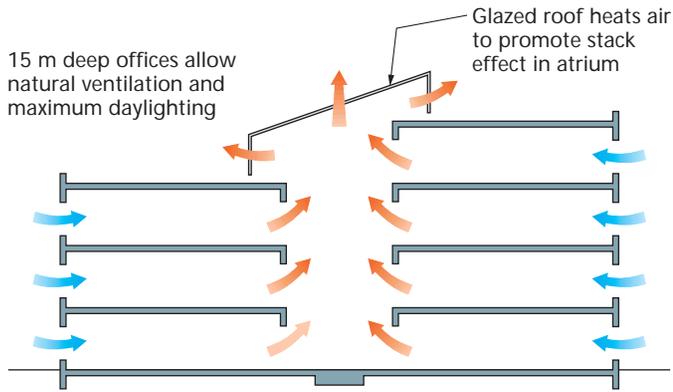
Figure 2.25 Atrium stack ventilation (Barclaycard Headquarters)

All of these features are built into the ventilation strategy of the BRE Environmental Building, see Figure 2.24. A more detailed description of the design strategy is given elsewhere[19].

Chimneys provide no functional purpose other than ventilation. Consequently they are sized just to satisfy the pressure drop requirements. They can be in the form of a single linear chimney or several smaller chimneys distributed around the building to suit the required ventilation flowpath. For example, if the building faces on to a busy road, it would be possible to place the inlets on the facade away from the noise and pollution source with the chimneys on the road side.

2.4.3.2   Atrium ventilation

An atrium is a variant on the chimney ventilation principle. The essential difference is that the atrium serves many additional functions. For example, it provides space for circulation and social interaction. Because it provides attractive, usable space, the location of the atrium is an integral part of the organisational planning of the building. The design of atria is discussed in detail by Saxon[29]. The multiple-use nature of the atrium restricts the flexibility to locate the atrium to maximum advantage for ventilation purposes, since many other criteria now have to be satisfied.

A significant advantage of atrium ventilation is that, as shown in Figure 2.25, the air can be drawn from both sides of the building towards a central extract point, thereby effectively doubling the plan width that can be ventilated effectively by natural means. (The same effect could be achieved by a central spine of chimneys.) It should be noted that the flow pattern as shown could not be maintained by stack effect alone, since the air could not pass through the top occupied level and exit through the atrium roof at the same vertical height level unless wind effects were also present.

The atrium also provides the opportunity of getting daylight into the centre of a deep plan building. If the atrium can provide good daylighting to its adjoining occupied space*, then much of the occupied space can be daylit for much of the time. The atrium can also act as a buffer space to reduce winter conduction losses from the surrounding accommodation.

Because atria are usually designed to capture natural light, they are in effect large solar assisted chimneys. The

* Note that penetration of daylight will be reduced at lower floors
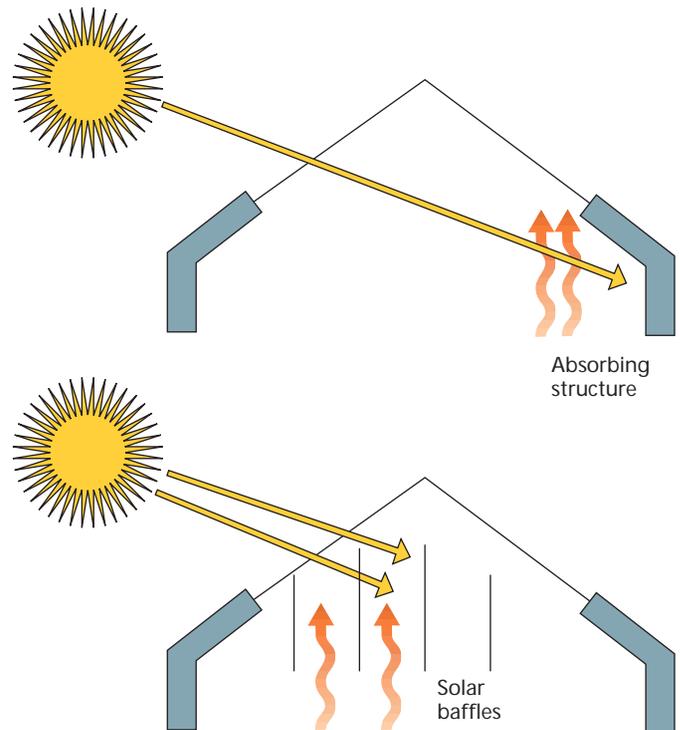

Figure 2.26 Absorbing solar gain at high level

particular strategy for capturing solar gain within the atrium will depend upon the precise function of the atrium itself. To promote natural ventilation, the air in the atrium should be as warm as possible for as great a proportion of the atrium height as possible. If the atrium is open to the surrounding space, or if it provides high-level walkways between floors, then excess temperatures at occupied levels may be unacceptable. In such situations, the design should seek to promote a stratified layer of warm air above the occupied zone by capturing the solar gain at high level on absorbing surfaces, which can then convect heat to the adjacent air†, see Figure 2.26. These absorbing surfaces could be:

—   elements of the structure

—   solar baffles or blinds which act as shading devices to prevent direct solar gain passing through the atrium to the occupied spaces; the baffles can be arranged to allow a view of the sky allowing good diffuse lighting without excessive glare.

It should be noted that the effectiveness of a solar chimney is determined more by the length over which the elevated temperature is maintained than by the magnitude of the temperature elevation. This means that, unless the elevated temperature can be maintained over a reasonable vertical height, the driving pressure for ventilation will be low. Therefore, if the design is seeking to achieve a high-level stratified layer, then the stack outlet will need to be higher than would otherwise be the case. This effect can be explored using the equations in section 4 that deal with stratified stacks.

As with the chimney strategy, the roof vents must be carefully positioned within the form of the roof so that positive wind pressures do not act on the outlets. It is normally possible to organise the outlets such that they

† Note that enhanced stack pressures only act across that part of the stack that is at the elevated temperature; this is known as the 'stratified stack' effect, see section 4

are always in a negative pressure zone. This is achieved by either:

— designing the roof profile so that the opening is in a negative pressure zone for all wind angles, or

— using multiple vents which are automatically controlled to close on the windward side and open on the leeward side.

Natural ventilation can be supplemented on hot still days by the use of extract fans in the atrium roof. Subject to Fire Officer approval, these might also form part of the smoke control system, although the vent would then have to comply with all the necessary performance standards for smoke ventilation.

2.4.4 Double-skin façade ventilation

The double-skin façade is a special form of solar chimney where the whole façade acts as an air duct. The main aim is to provide a very transparent envelope, but to trap the solar gain in a cavity between an inner and outer skins, and then ventilate the heat away to outside before it can have a significant impact on environmental conditions in the adjoining occupied space.

In most cases, it is the cavity between the two façade layers that is driven by natural ventilation as a means of removing the solar gains absorbed on the blinds. However, there are some designs where ventilation air can be taken from or exhausted to the cavity[30]. Figure 2.27, illustrates the 'shaft-box' façade. A particular benefit of this approach is that it provides a practical means of naturally ventilating

tall buildings by subdividing the building into a number of separate vertical stacks

Such designs are a specialist subject and so the reader is referred to a specialist publication[30] for further information. As well as the thermal and lighting performance of the façade, particular issues for consideration include condensation and fire and smoke spread.

2.4.5 Mechanically assisted strategies

The previous sections have described strategies that are essentially natural, but which can use mechanical means to supplement the ventilation during hot extreme weather. Other approaches rely on mechanical ventilation for the supply or the exhaust side of the system during normal operation.

For example, one approach is to use mechanical supply ventilation with natural exhaust. Such an approach may be required in very deep plan spaces where it is impossible to arrange all the occupied space to be within the required distance of the natural ventilation inlet. Mechanical supply, usually via an underfloor displacement ventilation system, is used to ensure good distribution of the fresh air. The air then rises within the space and is exhausted at high level into a chimney or an atrium. This approach also allows the building to be sealed against external noise or pollution sources.

With this approach, all the exhaust air is extracted at a common point. Because of the design strategy, that air will be warm, thereby providing the potential for heat recovery when required.

Mechanical extract/natural supply systems are most appropriate if there are particular areas where there are significant sources of internal pollution (e.g. 'wet' rooms, print facilities, smoking rooms etc.). The pollutants are removed at source and the precise route for the ventilation air is more controllable.

2.4.6 Night ventilation

Night ventilation is not an additional mode of ventilation; rather it is a different operational strategy. Night ventilation takes advantage of the natural diurnal variations in temperature to promote ventilation cooling. Night ventilation offers many advantages:

— Because of the lower night-time temperature, the inside–outside temperature differences will be greater, enhancing both the stack driven flowrates and the cooling capacity of the outside air.

— By cooling the fabric of the building by night ventilation, there is a reduction in the mean radiant temperature of the space, which enhances the occupants' perception of thermal comfort during the following day.

— By ventilating during unoccupied periods, the potential problems of draught and noise in the occupied space are avoided. However, if mechanical night ventilation is used, then the noise impact on neighbouring buildings must be considered, especially as background noise levels will be lower.
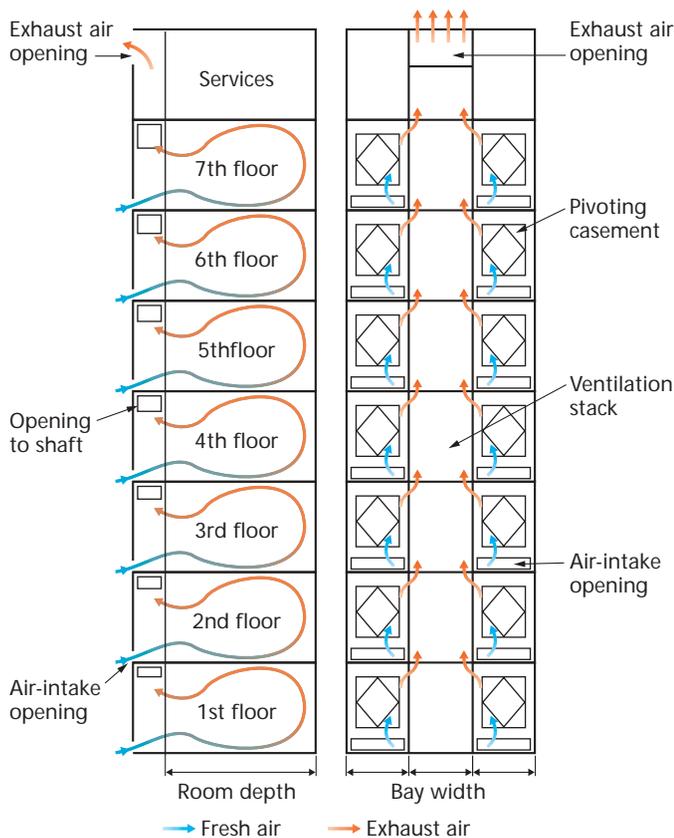

Figure 2.27 Shaft-box double-skin façade (reproduced from *Double-skin façades*[30] by E Oesterle, R D Lieb, M Lutz and W Hausler)

Night ventilation involves some additional issues that need to be considered as part of the briefing and design processes. These include the following:

— Night ventilation via opening windows is a security risk; this can be overcome by using opening limit devices, separate ventilation openings (such as motorised dampers or louvers), or a mechanical system.

— Appropriate controls are needed to avoid over-cooling the space, with subsequent discomfort the following morning.

— Good thermal contact (and thus high heat transfer rates) must be ensured between the ventilating air and the thermally massive elements of the building (usually the underside of the floor slab). Guidance on how to provide thermal mass in the building fabric and how to provide the necessary thermal contact with the ventilation is given in BRE Digest 454[31].

These issues are discussed in some detail in section 4.7 of Guide B2[2], which includes a number of design strategies for achieving thermal contact between the mass and the space.

3 Ventilation components and system integration

3.1 From strategy to specification

Achieving successful natural ventilation (whether manually or automatically controlled) depends critically on the detailed design, specification, installation, commissioning, operation and usability of the ventilation components and on the careful integration of the ventilators, actuators and controls. The key areas requiring attention to detail are:

— the principles upon which the system is designed and developed

— the products which are specified

— the processes of design, specification, installation, commissioning, and operation.

3.1.1 Principles

The purposes of the ventilation and control strategy need to be effectively thought through: how will the system be controlled and managed and how will individual occupants be affected by and interact with the system and its various components? These strategic issues are dealt with in section 2.

3.1.2 Products

The design challenge is to seamlessly combine components and subsystems that are often developed for different contexts. The various components and subsystems that need to be considered include the following:

(a) Windows, ventilators and rooflights which initially may have been designed solely for manual control.

(b) Actuators intended for occasional use, as in smoke ventilation, or developed for other purposes such as mechanical ventilation systems, greenhouses and industrial ventilators.

(c) Dampers normally used in mechanical ventilation systems. Although tried and tested in mechanical ventilation applications, when used for natural ventilation dampers can fall short of expectations in terms of appearance, building-in details and workmanship, insulation and airtightness when closed.

(d) BMS systems, and the way they are integrated with the manual control that is often desirable in naturally ventilated buildings. For example, providing manual control of windows by the occupants at low level and automatic control of high level vents where they are either out of sight or difficult to reach. BMS software must anticipate manual interventions and allow for these within its control logic.

Different types of actuators will be appropriate in different situations. The range of types available and the factors influencing choice are described in section 3.5. It is vital, however, that the link between actuator and ventilator is not overlooked. The following questions should be considered:

(a) Is it properly connected to the opening element and to the frame or building fabric?

(b) Are its connection points and fixings strong enough and are any linkages properly aligned?

(c) Will the element it opens close and seal effectively?

(d) How does it connect to the control system and to supplies of pneumatic or electric power? In one building, the need for such cables had been forgotten and it proved too difficult and expensive to retrofit them.

(e) Will it stand-up to the duty cycles required? Care needs to be taken so that the automatic control system does not constantly exercise the actuator, leading to a very short service life.

(f) Can it be maintained safely and conveniently?

There are fewer such questions when the opening, actuator and controls are procured as a fully integrated system, so that installation can be largely maintenance-free. Even then it can be important to check whether products have been adequately developed: manufacturers sometimes 'bolt on' actuators to standard natural ventilation products without sufficient thought.

3.1.3 The decision making process

Decisions need to be made in different parts of the supply chain, for instance:

(a) Who specifies what? An architect will often specify the window and a services consultant the actuator and control. Will they be compatible? How will they be put together? What about structural engineering issues?

Night ventilation involves some additional issues that need to be considered as part of the briefing and design processes. These include the following:

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(d) How does it connect to the control system and to supplies of pneumatic or electric power? In one building, the need for such cables had been forgotten and it proved too difficult and expensive to retrofit them.

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3.1.3 The decision making process

Decisions need to be made in different parts of the supply chain, for instance:

(a) Who specifies what? An architect will often specify the window and a services consultant the actuator and control. Will they be compatible? How will they be put together? What about structural engineering issues?

(b) What are the implications for construction programming and commissioning? Should the actuator be fitted at the factory or on site? Site fitting has often given rise to problems with mechanical integrity, alignment and fine adjustment (e.g. of end-limit switches). Some suppliers have a better record than others. Insist that site fitting is by specialists, and planned in advance.

(c) What about trade responsibilities? Ventilation openings, which are usually seen as part of the building fabric, now become part of the building services. This may bring trades together at stages and in sequences in which they would not normally be collaborating. Do specification documents and management of subcontract packages take proper account of this? There are many advantages if the window supplier is given responsibility for integration of vent, actuator and control. See Example 3.1.

(d) Have preparations been made for effective operation, management and fine-tuning? Occupiers often assume that natural ventilation will look after itself and so are not prepared to operate the controls. In addition, neither they, nor the designers or installers, make provision for the fine-tuning that is normally needed during the first year or so of operation. While the desirability of such activities is not unique to natural ventilation systems, they tend to be more critical to its success.

Having developed a clear overall ventilation strategy as early as possible, it must be kept under review. The following questions should regularly be revisited.

(a) How will local and automatic controls be integrated? The need for local override by occupants must be carefully considered. Generally, vents which are out of sight of the occupants are automatically controlled and not normally subject to local override. Conversely, high level vents which are visible should have local override control. Feedback on vent status is crucial.

Example 3.1 Offices for a housing association

The windows on the south side include fixed, manually-operable and motorised elements with concealed provision for actuators, controls and wiring. The actuator's chain drive attaches to the window at the same point as the manual latch, making secure fixing easier and helping the windows to close tightly. With tried-and-tested, factory-assembled components integration was assured and the installation has been virtually trouble-free.
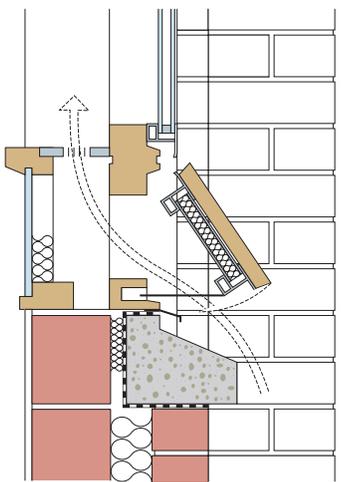
The initial outcome was less fortunate on the north side, which used purpose-made motorised flaps and concealed dampers in site-built enclosures beneath louvres in the window cills. Here integration was less easily achieved with air leakage both through and around the dampers. Unclear indication of control status caused problems, particularly with heat loss and discomfort in winter.

(b) How many different types of ventilation device will be required to cope with all seasonal and occupational requirements?

(c) How will ventilator geometry affect available free area and airflow rates?

(d) Will they seal well when closed?

(e) Will they clash with other devices, e.g. fixed or movable blinds?

(f) What protection will be required against high winds and rain penetration?

(g) What restrictions are there in terms of noise and security?

(h) What actuators and linkages will be used and how will they be integrated and fixed?

(i) Is protection against insects and small animals required?

(j) What controls and feedback devices will be provided for occupants and management?

(k) What provision has been made to promote occupant awareness of the system?

(l) Has a clear division of responsibilities for all aspects of the ventilation and control scheme been established?

3.1.4 Responsibilities for effective integration

Clear division, definition and ownership of responsibility is vital for a successful outcome. If the boundaries of responsibility are not clearly defined, some problems may not be 'owned' by anyone. Important elements may even be left out of the specification entirely. For example, a factor often overlooked is that ventilators (usually specified by the architect) and actuators (often specified by an engineer) are joined by linkages. Experience suggests that in many installations, linkages and fixings are major points of weakness and sometimes complete failure.

For window-type ventilators, the architect will normally specify the ventilator and the building services engineer the actuators and control system. Contractually, where the actuators form part of the window package, the window manufacturer becomes responsible for procuring and fixing the actuators, and for testing the performance of the integrated assembly. This will allow many problems to be solved before the assembly arrives on site. Even if some site assembly (e.g. installation of projecting actuators) is required, it will have been more carefully planned.

To prepare a complete specification for an integrated window-type assembly, the architect will need to obtain specification information on actuators, controls, linkages and fixings from the engineer. In order to be able to judge the appropriateness and completeness of this specification, the architect will need to be aware of all the criteria that need to be covered.

Sourcing from a single manufacturer can help to eliminate the risk of integration problems but this is not essential. However, successful integration of ventilator, control,

actuator and linkage components from different manufacturers requires:

(*a*)   a knowledge of the technical issues, and

(*b*)   clear lines of responsibility.

Window and actuator suppliers all recommend early dialogue during which issues can be raised, e.g. providing suitable fixings for the actuator, suitable linkages, the need for any reinforcement of the frames. It is also recommended that the window/ventilator supplier be asked to supply shop drawings showing the actuator type, linkage and fixings.

For damper-type ventilators, the building services engineer is more likely to specify the assembly, complete with its actuators and controls, while the architect will be concerned with its appearance, finish, weather-tightness and building-in details. Ideally, a detail will be developed which allows the damper assembly to be simply inserted as an engineering item into a prepared opening in the building specified by the architect.

The responsibility matrix, Table 3.1 (pages 24 and 25), identifies the various issues in the design that need to be considered, and the interactions between the different members of the client/design team that will be necessary to ensure appropriate design solutions are developed in relation to the specification of vents, actuators and controls. This can form a useful 'aide memoire' for the team during the detailed development of the design.

3.2   Ventilation opening types

Having defined the ventilation strategy (see section 2) the type of vent opening type needs to be chosen. Natural ventilation openings are of three broad types:

(*a*)   Windows, rooflights and doors

(*b*)   dampers or louvres

(*c*)   background 'trickle' ventilators

3.2.1   Windows, rooflights and doors

Their major advantages are that they are familiar to occupants and that hinged versions can be made to shut tight relatively easily. In comparison with louvres and dampers:

(*a*)   they have a shorter crack length

(*b*)   effective seals are easier to provide

(*c*)   closing forces can be higher and better distributed about the perimeter.

Window stays vary widely in terms of their 'throw', geometry and robustness. Particular care must be taken to ensure that the effective free area is achieved (see section 2 and *Ventilation capacity* below). Most patterns of window and door were originally designed for manual operation. Windows used for automatic control may require adaptation to accept motorised actuators, and need strengthening to accommodate forces applied at different places and in directions that may not be parallel to that in which the window opens.

Different window designs may be assessed under the following criteria:

(a)   *Ventilation capacity*: this is clearly related to the way the window opens and the surrounding head, cill and jamb details. Determining the effective area for a particular window type must be done carefully to ensure a sound basis for subsequent calculations of volume flow rate. With top hung vents, for example, the triangular opening each side of the open window is significant; in the event, an estimate is usually the basis for calculations. Figure 3.1 illustrates the difference between structural opening, throw, and effective opening. Window sills, reveals, internal and external blinds all have a major impact on the final effective area which is achieved. Ensure that the strategy is carried through into detail design by providing continuity in the design team. Table 3.2 (page 26) considers the ventilation capacity of different window types.
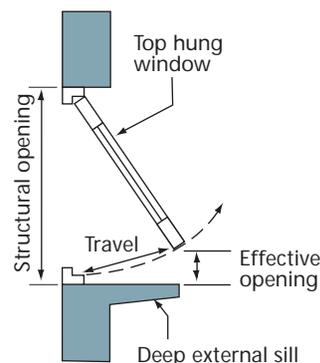

Figure 3.1 Structural opening, effective opening and travel distance for a top hung window

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Example 3.2 Automated fanlights at Building 16, BRE Garston

(courtesy of Feilden Clegg Bradley Architects)

Contact between the incoming air and the building structure is enhanced by using a 'wavy' ceiling slab that allows night air to pass through it. The automated fanlights at the perimeter use chain drive actuators.

Hand-held infra-red controllers permit users to over-ride not just the automated windows but also the external louvres and the electric lighting from any point within the space. In spite of this good control, occupants have commented on insufficient feedback owing to the slow response times of windows and louvres, and not being able to see the automated windows which are behind the low points of the 'wavy' ceiling profile.

(*b*) *'Controlability'*: where it is considered desirable and acceptable for occupants to control opening of windows, stays should be both adjustable and robust. With manual and automatic operation, the stay increases the angle of opening of the window and the effective area will increase, but the relationship is not linear, and this will also vary according to the opening type[32].

(*c*) *Comfort*: generally, the use of opening windows results in high levels of user satisfaction when local occupant control is part of the strategy. However, the use of the same opening for winter and summer ventilation may be unsatisfactory in certain situations. Where, for economic or other reasons, this approach is taken then the impact of the window geometry on draughts in winter or movement of papers in summer must be considered. This can be a reason for maintaining low level openings under manual operation and high level openings under automatic control. The provision of automatically controlled high level window openings for night ventilation can incorporate manual override to provide occupants with a greater degree of daytime control.

(*d*) *Security*: it can be argued that open windows are only likely to be a security problem at ground or first floor levels of a building. Restricting the length of throw of stays or actuator arms may be sufficient in many situations. A facility to lock manually opening vents in a secure position should be provided.

(*e*) *Sealing*: sealing of windows is usually achieved by EPDM expanded rubber gaskets. In aluminium framed windows the tolerance achieved is usually very fine and good sealing is achieved. However, with some steel framed and timber windows, racking or twisting of the frame can occur, particularly with large windows, resulting in poor sealing. Automatic vent gear must be installed so that the opening frame is pulled tight against the subframe.

(*f*) *Integration with vent actuators*: the choice of window type and its integration with different actuator options and (where applicable) internal blinds, requires careful consideration if the performance of one or other of these components is not to be compromised.

The main window types and related automated actuator options are described in Table 3.2 (page 26).

3.2.2 Dampers or louvres

Motorised dampers are widely used in mechanical ventilation systems, where they are usually effective and reliable. However, when used for natural ventilation they have a major disadvantage in that they do not shut as tight as most windows: this is due to:

— longer crack lengths

— difficulties with rotating seals

— problems with mechanical strength and closing forces.

Additionally, they are often characterised by poor insulation standards, with subsequent condensation problems.

In many naturally ventilated buildings constructed in the last 15 years, excessive air infiltration has caused problems with heat loss and discomfort in winter. Some available products, including some glass louvres, have good seals but need to be carefully selected and checked for construction and performance.

For most dampers, the shaft for the actuator motor projects out of the frame, from the end of one of the damper shafts. This is ideal for ductwork and air handling units as the motor can be installed, checked and maintained externally. However, for natural ventilation, the projecting shaft stops the dampers being installed in the plane of a wall, so either the dampers need to be fitted within a duct spigot or lever operation may be necessary.

The different damper types which may be used for natural ventilation are described in Table 3.3 (page 27).

3.2.3 Background trickle ventilators

Trickle ventilators are designed to provide a minimum fresh air rate, but are designed to be controllable (and can be shut down) particularly in winter. Building Regulations Approved Document F*[4] recommends an opening area for background ventilation which is related to floor area, with a minimum provision in all habitable rooms of 4000 mm². Trickle ventilators can be in the window frame, part of the glazed unit or independent of the window. Adequate winter ventilation can also be achieved by an automatically controlled window element. See Example 3.3 (page 27).

To minimise cold draughts, the ventilators should be at high level (typically 1.75 m above floor level) and designed to promote rapid mixing with room air. As trickle ventilators are only intended to promote 'background ventilation' (about 5 litre·s⁻¹ per person), their main purpose is to supply fresh air in winter months. The apparent need for control, even over trickle ventilators, has led to the development of pressure regulated trickle ventilators that respond to variations in pressure differences around the building, especially during periods of high wind speed. Their advantage is that they throttle down in windy weather, but still require further development and there are only a few products currently on the market.

3.2.4 Combined openings

When designing ventilation openings, it is common to use combinations of opening types in an overall design. For example, motorised dampers or louvers may be used to control fresh air supply to an underfloor plenum, and then to a space from which air is exhausted via high level windows.

Different opening types may be combined in a single window unit (e.g. an opening window with a trickle ventilator in the frame), or they may be independent. Combinations of window types in a single window unit are worth considering. For example, a hopper over a centre pivot window has many advantages. The hopper can provide night ventilation and also help provide air to occupants deep into the room. The centre pivot allows high summer ventilation rates and is especially beneficial
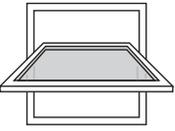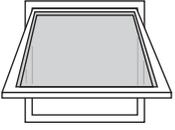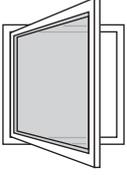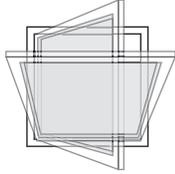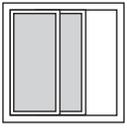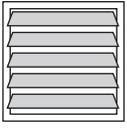
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* Under review at time of writing (January 2005)

Table 3.1 Principal responsibilities and interactions

Category	Client (owner)	Architect	Building services engineer	Client (facilities manager)
Briefing	Define: — site/location — activities — occupancy — performance criteria — control preferences	Comment on: — area/volume requirements — plan depth/massing — orientation — spatial relationships — performance criteria	Comment on: — performance criteria	Comment on: — performance criteria
Ventilation strategy	Take ownership of strategy Question implications for: — lifecycle cost — occupant satisfaction — control options — CDM issues	Define relationships of supply and exhaust for different purposes: — zoning — airflow paths — geometry — application of principles — CDM issues — operational instructions	Define flowrates to achieve: — indoor air quality — cooling — local extraction of pollutants — control Pre-commissioning CDM issues Draft simple instructions for users	Question implications for: — occupants satisfaction — operation — maintenance — CDM issues
Ventilation openings	Implications for: — appearance — operation — maintenance — access — replacement	Preliminary sizing of vent openings Opening type Weathering Security Clashes with other elements Airtightness/thermal performance Interface with building envelope	Preliminary sizing of ventilation openings for supply and exhaust Performance prediction in relation to briefing criteria Pollution and noise control Access for maintenance	Access for: — commissioning — cleaning — maintenance
Actuator		Implications for: — appearance — achieving required free area opening — achieving required ventilation purpose	Choice of type in relation to: — weight and size of openings — type of opening — location (low or high level) — opening parameters	Implications for: — operation — maintenance — replacement
Linkage		Number of openings operated Geometry and connections Maintenance and cleaning	Commissioning requirements Maintenance and cleaning	Implications for: — operation — maintenance
Controls	Implications of control and logic for occupant operation and satisfaction	Control logic Operation during construction Status feedback	Control logic: — status feedback — automatic/normal/fire modes — occupant override — wind/rain/snow thresholds	Implications for: — operation — maintenance
Installation and commissioning	Recognise importance Ensure time in programme	Recognise importance Ensure time in programme	Commissioning requirements Access Witnessing	Access for commissioning Commissioning requirements
Operation and maintenance	Allow for training		Fine tuning Simple user instructions	Fine tuning CDM issues

Specialist subcontractor or product designer	Contractor	Comments
		The structure of this table assumes a conventional contract. Where the contractor is engaged in design then the responsibility chain will change.
		It is important that all involved take ownership of the agreed strategy. This includes the quantity surveyor. Elements which are fundamental to the working of the building cannot subsequently be regarded as optional extras in cost cutting exercises.
Implications for: — actuator type — linkages and fixings — effective area achievable — frame reinforcement	Subcontract package boundaries, coordination and programming Advise on maintenance procedures	Generally the vent supplier should be made responsible for integration of vent with actuator linkage and controls.
Implications for fixings: — frame reinforcement — noise — speed of operation	Recommend that actuators form part of the window package where appropriate	Engineer must also allow for power and control requirements and circuiting, as well as maintenance, alteration and replacement.
Advise on: — forces acting on fixing points	Check linkages and fixings have been defined by design team	Where vent, actuator and control are not integrated, the architect will become responsible.
Pre-commissioning demonstration of system		
Undertake commissioning according to commissioning plan	Commissioning requirements Ensure time in programme CDM issues Supply O&M manuals	Allow for modifications during first year of operation.
Undertake maintenance		

Table 3.2 Main window types and actuator options

Window type	Actuator options (if automatic control is required)	Comments
Horizontal pivot	Linear Chain	These windows have a high ventilation capacity and the geometry promotes good distribution of supply air. Internal blinds are not practical but interpane blinds may be a useful alternative. For an opening of 22° then the effective area is 34% of the area of the structural opening. Shorter stay length compared with casements, reduces wind pressures on actuators.
Vertical pivot	Linear Chain	This type provides a similar effective area as horizontal pivot. Internal blinds are also not practical Vulnerable to driving rain, and will provide a 'wing wall' effect (either positive or negative) in response to the prevailing wind.
Top/bottom hung	Linear Chain Rack and pinion Lead screw Lever arm	Wider range of actuator options. Length of throw is significantly increased relative to pivot windows. (i.e. more costly and more vulnerable under high winds). Although bottom hung inward opening is a useful geometry when located adjacent to the ceiling for night vent cooling, top hung is a better geometry at low level to direct flow towards occupants for daytime ventilation.
Side hung (casement)	Chain Rack and pinion	Not easy to link to automatic opening gear (lever arm must rotate as it extends). Also ventilation characteristics are strongly influenced by wind speed and direction (as with vertical pivot windows).
Tilt and turn	Cannot be linked to actuator	These ventilation characteristics have been studied in several buildings, where it was reported that the 'tilt' setting provides too much ventilation in winter and insufficient cooling for occupants in summer.
Sash (sliding)	Linear Linear sleeved cable or rod	These windows have ventilation characteristics similar to the vertical and horizontal pivot window. The effective area is maximum 50% of the structural opening.
Louvres	Rotary Linear	Usually glazed or aluminium. Advantages are that they can be made secure and still function satisfactorily, and therefore have potential application for night ventilation. However, when closed louvres generally have a very poor seal. This is the case with most louvre or damper installations.

to occupants near the perimeter. The different sizes of opening also allow finer control over the ventilation rate by progressively opening the hopper and opening the main window, then opening both together.

As the design of the unit is developed, the other functional requirements of the window (lighting, shading, security, transmission losses) need to be considered. Considerable effort is being put into developing multi-function windows that address all these requirements.

Many ventilation strategies rely on shafts to take air vertically through a building. Similarly, ducts (including floor voids) are used to provide horizontal distribution. The criteria for sizing these airways are very different from those for conventional mechanical ventilation system because of the need to keep pressure drops within the range available from natural driving forces. This means that space must be allowed to incorporate larger than usual ducts or shafts.

Table 3.3 Types of damper suitable for natural ventilation

Damper type	Construction	Comments
Standard blade	Standard dimensions: heights/widths from 100 mm to 2400 mm in steps of 100 mm. Bespoke sizes available. All dampers have a position indicator and manual adjustment device.	Mainly used for mechanical ventilation systems and can be installed in either rectangular or circular ductwork. This is also provided with a motor platform. This type of damper is used to control ductwork volume flow rates in connection with ductwork balancing.
		Can provide control in natural ventilation systems. In the closed position the leakage air flow of a closed damper is low (though higher than a window). In the open position the blades are turned in the direction of flow and do not cause a significant pressure loss.
Sealed blade	Normally supplied with a motor platform. Available in diameters from 100 mm to 1000 mm or rectangular in heights/widths from 100 mm to 2400 mm in steps of 100 mm.	Often used to close a ductwork branch, as in the closed position the leakage air flow is low. In the open position the blades are turned in the direction of flow and do not cause significant pressure loss. Can also used for the control of volume flow rates.
		Has better sealing than standard damper type. Consists of a casing and blades usually made of painted hot-galvanised or acid-proof steel. There are gaskets built into the edges of the blades and between the end of the blades and the outer frame.

Also of crucial importance is the need to keep the inlet ducts clean to minimise problems of poor air quality. This will require the provision of inlet screens and access for cleaning.

Since shaft outlets are at high level, they are in a region of higher wind speed. This means that the wind pressures acting on the shaft are also likely to be high. Wind effects will probably dominate the pressure distribution through the system, except at very low wind speeds. It is vital, therefore, that outlets are designed to create wind pressures that reinforce the intended flow direction. Usually, this means creating a negative pressure coefficient at the top of the shaft, the exception being the wind scoop, see Example 3.5 (page 28).

3.2.5 Shafts and ducts

Orme et al.[33] provides information on the required pressure coefficients. For isolated buildings with no local flow interference, the minimum height of the stack above roof level to avoid back-draughting is given by:

$$h = 0.5 + 0.16 (\theta - 23) a \qquad (3.1)$$

where h is the height above roof level (m), θ is the roof pitch (degrees) and a is the horizontal distance between the outlet and the highest point of the roof (m).

Occasional back-draughting may not be regarded as a problem, depending on the situation.

For roof pitches of less than 23 degrees, the outlet must be at least 0.5 m above the roof level. This simplified relationship represents a minimum stack height, greater heights may provide higher suction pressures. This can be beneficial, since a tall shaft can generate a suction greater than that generated on an opening on the leeward vertical face of a building.

More information on the pressure coefficients over roofs is given in BS 6399[34]. Model testing is available for complex roof profiles or where surrounding buildings or other obstructions disturb the wind.

As well as the position of the roof outlet, the geometry of a cowl also affects the pressure coefficient. The cowl should prevent rain entering the stack; it can also accelerate flow close to the outlet to reduce static pressures.

3.2.6 Ventilator design decisions

A preliminary list of items that need to be considered by designers is given in Figure 3.2 (page 29), which may be photocopied and used as a checklist.
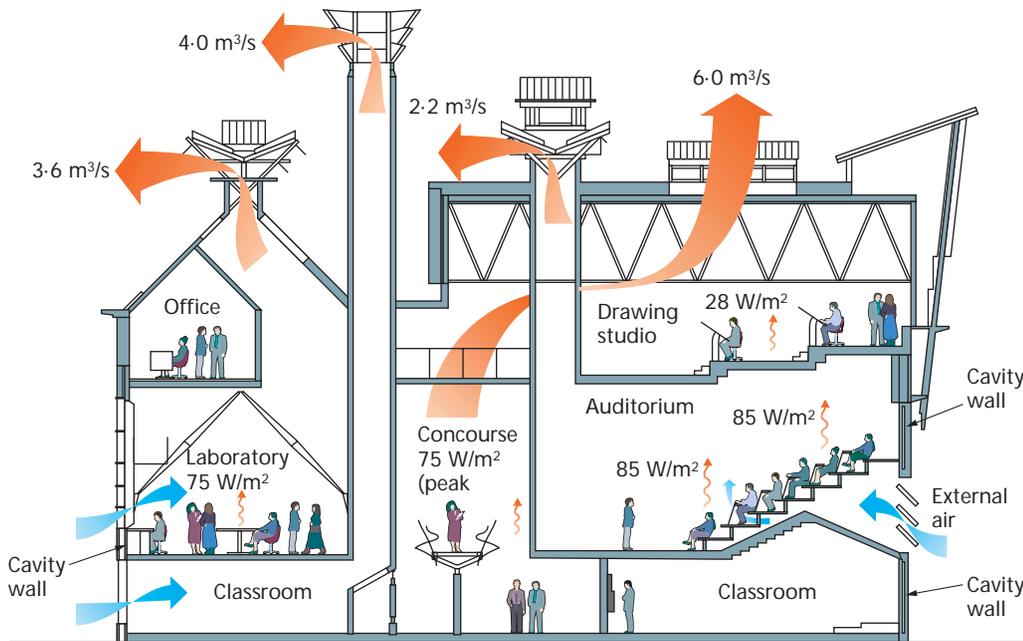
3.3 Internal obstructions

Windows and ventilation openings create resistances to airflow where the air enters or leaves the building. In series with these flow resistances will be internal resist-

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Example 3.3 Natural ventilation of corporate offices on a 'green field' site
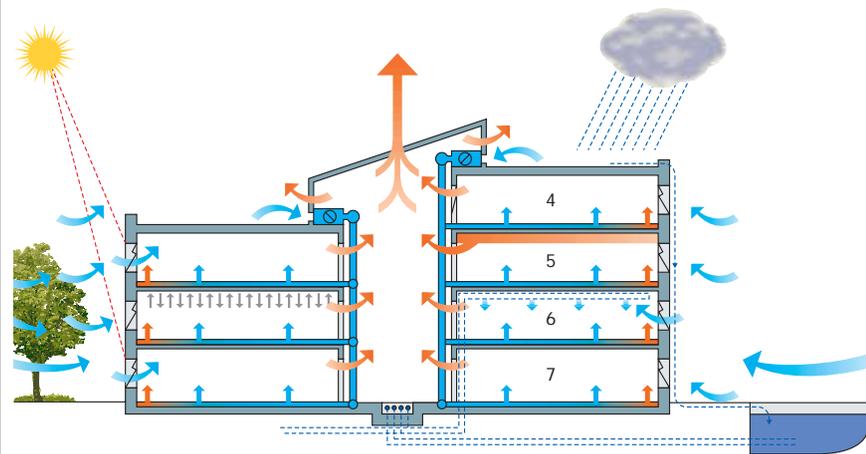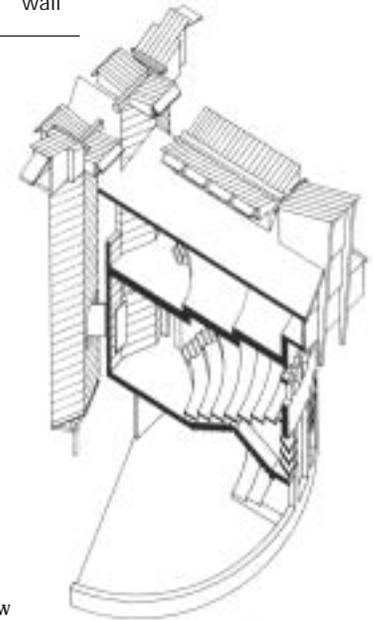

This office building used fixed trickle ventilators and natural ventilation to maintain indoor air quality, plus a mechanical system (supplemented by chilled beams) for summer cooling. In practice the amount of trickle ventilation has proved excessive, and sometimes draughty, and many of these ventilators have now been blocked-up. However, in other respects natural ventilation via the atrium is working well. High level atrium vents are operated by paired pneumatic actuators.

Example 3.4 Vertical shafts and terminations used to enhance natural ventilation; Queen's Building, de Montfort University (courtesy Short Ford Architects)

4·0 m³/s

2·2 m³/s

6·0 m³/s

3·6 m³/s

Office

Drawing studio

28 W/m²

Cavity wall

Laboratory 75 W/m²

Concourse 75 W/m² (peak

Auditorium

85 W/m²

85 W/m²

External air

Cavity wall

Cavity wall

Classroom

Classroom

Cavity wall

Detail of termination (photo: B Ford)

Isometric view

Example 3.5 Wind cowl at the Jubilee Campus, University of Nottingham (courtesy Hopkins Architects)

ances created by internal partitions and doorways etc. Thus, the way the internal spaces are compartmentalised into individual work areas needs to be considered as part of the overall ventilation strategy. (Resistances are discussed in detail in section 4.)

If cross-ventilation is employed, care needs to be taken to ensure that the ventilation path is not obstructed by full-height partitions and closable doors. If cellular office space is required, transfer grilles will be needed, as a minimum, to allow the air to move across the building. The resistance of these transfer grilles will need to be included in design calculation when sizing the façade openings.

As well as providing a resistance to the airflow, internal partitions, furniture, filing cabinets etc. can influence the airflow pattern. Where this occurs, the occupant does not experience the full benefit of the fresh air, since it bypasses the occupied space, moving across the space at ceiling level. This is directly analogous to the problems that can occur in mechanical ventilation system if obstructions are placed between the supply diffuser and the occupant's work place.

Ventilator design checklist

☐ Types of ventilators to be used

☐ Sizes of the individual openings (effective area) for winter and summer use

☐ Loadings, both in normal service and in extreme situations, e.g. high winds

☐ Influence of ventilator geometry on free area and airflow rate

☐ Actuators and linkages to be used, and their integration and fixing

☐ Control strategy required, including appropriate integration of manual and automated controls, and the scope for user over-rides

☐ Need for feedback on operational status, both to individuals and to the control system

☐ Provision for control equipment and the associated transformers, compressors, switches, indicators, wiring and tubing; together with the associated safety and protection requirements

☐ Need to avoid adverse effects, such as ingress of noise, rain, fumes, insects and intruders

☐ Need to avoid clashes: physically (with internal curtains and blinds, external shutters and sunscreens, insect screens) and operationally (with building services systems)

☐ Health and safety issues in installation, operation and maintenance, particularly safe access for maintenance and cleaning

☐ Need to avoid hazards from unexpected operation, e.g. trapping fingers or knocking people over

☐ Need to avoid 'grey' areas of responsibility for design, installation, testing and commissioning.

Figure 3.2 Checklist: ventilator design decisions

3.4 Background leakage

It is very important to appreciate that purpose provided openings such as windows and ventilators are not the only routes through which outside air flows into the building. All buildings have leakage paths at joints between building components and through some building materials. The extent of these leakage paths can have a significant effect on overall ventilation performance since it is the size and distribution of the ventilation paths that controls the magnitude and direction of the airflow.

Background leakage is usually quantified by installing a pressurising or depressurising fan in an external opening and measuring the airflow rate required to maintain a target pressure differential across the building envelope[24]. Building Regulations Approved Document L2[5] now sets maximum allowable air permeability standards and, for buildings with floors areas greater than 1000 m^2, the achievement of the standard must be demonstrated by means of a pressure test.

For controllable natural ventilation, the CIBSE 'good practice' recommendation[3] is that the airtightness should

not exceed 7 $m^3 \cdot h^{-1}$ per m^2 of permeable envelope area for an imposed pressure differential of 50 Pa across the envelope ('best practice' = 3.5 $m^3 \cdot h^{-1}$ per m^2). To achieve these targets, careful attention needs to be given to the detailing of component jointing and sealing techniques. BRE has produced a report to give guidance on methods of reducing air infiltration in large, complex buildings such as offices[35]. The worst allowable for offices under Building Regulations Part L* is 10 $m^3 \cdot h^{-1}$ per m^2.

3.5 Window stays and automatic actuators

### 3.5.1 Actuator and linkage options

The types of automatic actuator commonly used for natural ventilation, together with their linkage options, typical applications, and comments on their suitability, are as follows:

(a) *Linear push-pull piston*: a motor propels a push-rod forward. These are most commonly pneumatic but electro-hydraulic versions are also available. Advantages include mechanical simplicity, robustness, fire resistance of pneumatic units and generation of large forces. Disadvantages include large projecting cylinders and mechanical damage to windows, linkages and fixings which are not sufficiently robust. Travel is typically 200–500 mm but longer distances are possible with large cylinders. They are most widely used for rooflights and high-level windows.

(b) *Projecting chain drive push-pull*: an electric motor drives a chain over a sprocket wheel, providing linear motion to push out a window. They are generally modest in size and mechanical strength; and with limited travel of typically 150–200 mm. A useful feature is that the motion tends to be at right angles to the axis of the actuator body, which can therefore be tucked away in the plane of a window frame or recessed and concealed within it. Their compact size and unobtrusive appearance makes them best suited to smaller windows such as inward and outward opening fanlights.

(c) *Rack-and-pinion*: a rotary electric motor drives a geared shaft which engages with one or more racks, providing linear motion with less bulky projections than linear actuators. Typical travel distances are 500 mm but travel distances of 1000 mm or more are possible. They are particularly useful for windows which require paired actuators (one on each side). With a common pinion, the two racks move together, which avoids twisting the window (as can happen, for example, if one of a pair of linear actuators fails; sometimes breaking the window). They are most commonly used for rooflights with relatively light frames.

(c) *Linear sleeved cable or rod*: driven by a rack-and-pinion, worm gear or chain drive electric motor and allow linear motion to be transferred, for example, to sliding sashes.

(e) *Rotary*: these are most commonly applied with dampers and louvres, often rotating one of the

* Under review at time of writing (January 2005)

Example 3.6 Bedales School Theatre, Hampshire (courtesy of Feilden Clegg Bradley Architects)
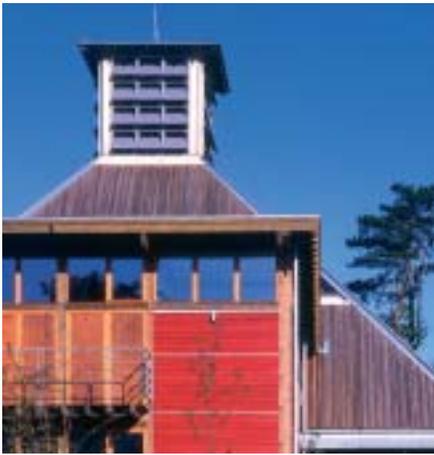
(*photo*: Dennis Gilvert)
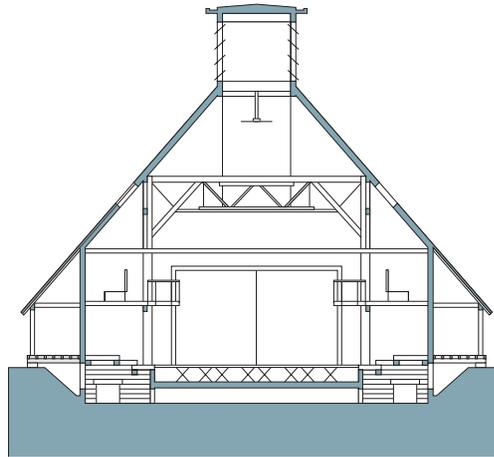
Five bays of vent openings on the north and south sides of the auditorium, located below raised perimeter walkways, supply air below perimeter seating via a plenum. These vents have fixed timber louvres to the outside with a double bank of fully modulating motorised vents behind. Performance is generally satisfactory. Early problems of draughts on north side have been solved, but at high level, poor adjustment of lever arms results in large gaps when in the 'closed' position. Infiltration losses due to large crack length of motorised dampers at low level, and poor sealing to high level window vents cause heating energy consumption to be higher than predicted.

shafts directly, with mechanical linkages to the other louvres. Sometimes they also operate shafts connected to cranks and lever arms to provide linear motion. There are two main types: one with a bi-directional motor used for opening and closing, and one which motors in one direction only and uses a spring to return, which can be useful for fail-safe operations.

(*f*) *Lead screw*: these actuators form the majority of linear actuators and are sub-divisible into high and low power applications. For general applications from 200 N to 2000 N, a low friction nut is driven along the lead screw to provide motive force.

(*g*) *Lever arm*: these often found in Victorian schools and hospitals. Continued use is testament to the robustness of the gear. It is often regarded as visually intrusive and unnecessarily cumbersome today (but are still being manufactured).

(*h*) *Gas struts with cables*: a linear variant on the spring return motor is where an automatic catch releases the window and a gas-filled strut opens it, or holds it open. Closure is then affected by pulling on a cord, either manually or by means of small electric winch.

3.5.2   Actuator and linkage selection

There are many factors that need to be considered when choosing an actuator. These include:

— *Location of vent and manner of opening*: there are three common variants: a hinged flap, a set of centre-pivoted louvres, and a panel sliding on runners. Linear actuators are most commonly used for rooflights and chain drives for low level windows, where it is more important for actuators to be unobtrusive and for them not to obstruct the interior.

— *Weight and size of vent*: the motor should be sized to support the appropriate level of forces, including wind, snow and ice loads. Large windows may require two (or more) actuators.

— *Angle of attack*: owing to geometrical restrictions, the actuator force cannot always be applied exactly in the direction of motion and can sometimes be

nearly at right angles to it. This can lead to large shear forces and moments on fixings.

— *Travel and free area to be achieved*: chain actuators are usually limited to 150–250 mm, though some concealed units can reach up to 500 mm. The chains have limited buckling strength, so they are most commonly used to open top or bottom-hung windows by a small angle. Linear piston actuators typically have travels up to 600 mm, while rack and pinion drives can go up to 1000 mm and more.

— *Available space*: actuators tend to swing as a window opens so articulated linkages are required. Actuator and linkage components must clearly not clash with each other, or with the surrounding structure, during their full range of travel.

— *Travel speed*: low travel speed is desirable to reduce loadings on the actuator and to reduce noise. However, where occupant control is used, visible response is also important so people can see that their control actions have had a result. If the actuator moves too slowly or is not visible from the point of operation, then some visual feedback such as an indicator light or display should be provided. For rooflights, rapid closure is desirable to minimise entry of rain. Two-speed operation may be desirable; slow for normal operation and fast for manual over-ride and emergencies.

— *Smoke ventilation*: sometimes the ventilator may need to open or close within a specified time. For example, smoke control often requires any ventilation device to be fully open within 60 seconds. For use as a smoke vent, the ventilation opening, actuator, linkage and controls must be tested as a complete package in accordance with BS 7346: Part 1[36].

— *Linkages and fixings*: linkages and fixings must be carefully considered for appropriateness, mechanical strength, durability and ease of installation and maintenance. The supplier of the ventilator should be made responsible for the fixing and mechanical commissioning of the actuator and linkage. This should include adjustment of any end stops and limit switches which, if not carefully done, can easily lead to mechanical damage to the actuator, linkages, fixings or ventilator.

— *Electrical safety/level of protection*: electrical actuators tend to be either 240 volt or 24 volt. The former is cheaper (but needs more relays) and the latter is safer (but needs transformers and larger diameter cables). Although normally indoors, some actuators may be exposed to high humidity, drips, or driving rain. Occasionally they may need to be flame or explosion proof (when pneumatic operation would be preferable). For electrical equipment, the level of protection is defined by the IP rating (from IP 00 to IP 68). The first digit refers to ingress of dirt and dust (from 0 (unprotected) to 6 (dust-tight)) and the second to ingress of water (from 0 (unprotected) to 8 (submersible)). Linear actuators in exposed positions might be IP 65 (dust-tight and protected against water jets from any direction) while chain drive actuators sheltered by an opening window might be IP 33 (resistant to objects above 2.5 mm, water drips, and water spray at an angle of up to 60° from the vertical). IP 54 is a reasonable cost compromise (particularly important for motor housing, but this may be difficult to achieve for chain drives). For products with a lower rating a secondary housing for the motor may be required.

3.5.3   Forces imposed on an actuator

The forces imposed are determined by:

— the weight of the ventilator

— external and uncontrollable forces especially wind, snow and ice

— the positioning of the actuator and linkage

— maintenance loads (sometimes).

How these forces are transferred to the actuator depends on the angle of the ventilator, the location of the fixing points, the geometry of the linkage (which will often change with the extent of opening), the geometry of the actuator, the speed of opening, and any frictional and adhesive forces.

3.5.3.1   *Ventilator weight*

The effect of self-weight depends on geometry. A rooflight will need a considerable force to open it (and to keep it open) but only requires the actuator to resist the weight during closing. A top-hung window will require much less force to open and to be resisted during closure, and a centre-pivot window even less. A bottom-hinged window will need very little effort to open, but may need a significant force to close, depending on the opening angle. If a fanlight is to open no more than 10–15°, then the forces required can be often met by a small chain drive actuator producing 500 N, with a maximum static load of twice the dynamic load, or 1000 N.

Issues to be considered are:

— the weight to be supported when shut and when fully open

— moments on pivot points when shut and when fully open.

3.5.3.2   *External forces*

Wind, snow and ice loads may often be far higher than the weight of the ventilator itself, particularly for rooflights. High suction loads may also require latches to ensure that the unit remains closed under extreme conditions. Rooflights used for smoke ventilation are required to operate under any conditions, including a once in 50-year occurrence (approximately 160 mm of fresh snow). If the system is for natural ventilation only, then there may be no requirement to open under snow load but this may still affect the design of actuators, linkages and safety measures to avoid actuator failure when attempting to operate under excessive loadings.

Issues to be considered include:

— snow, ice and wind loads in all positions

— possible requirement for catches to keep the ventilator secure in the closed position.

3.5.3.3   *Actuator position*

The positioning of actuators and linkages will often be affected by the size and shape of the ventilator, the availability of fixing points, the presence of obstructions, and aesthetic considerations. Angular and leverage effects can then multiply the forces on the actuator. The smaller the distance from the pivot point to the actuator, the greater the force required, but the shorter the stroke.

Issues to be considered include:

— multiplication of forces owing to actuator positioning and angle

— mechanical strength of the ventilator

— effect on specification of actuator, fixings, linkages.

3.5.3.4   *Other forces on the actuator*

Where possible, actuators should operate slowly. High speed operation will cause greater stresses on the unit and large shock loadings at each end of its travel. Where the actuator acts as a strut, holding the ventilator open, buckling loads will also need to be considered.

Engineering advice should be sought from the supplier of the assembly when analysing the forces on the mechanism. The complexity of predicting the performance of the different elements suggest that testing of the final assembly prior to final production is essential.

Issues to be considered include:

— dynamic and buckling stresses.

3.5.4   Number of actuators

Studies of a number of different installations[37] have revealed that a good general rule is to have one actuator per ventilator. If one actuator powers several ventilators, difficulties in obtaining good initial alignment, together with accumulating backlash in the linkages, nearly always means that not all the ventilators close tightly, leading to problems with airtightness and security. This can be aggravated by racking of the ventilator frames, distortions

from poor fixing, flexing of the linkages, lever arms and brackets or from shock loads from wind or at the ends of travel.

If the end stops are not correctly set, or drift as backlash accumulates, the more powerful motors necessary to operate multiple ventilators can easily run on beyond the end of the linkage's available free travel and cause damage to themselves, the linkages or the fixings. A current limit on the motors can be applied to prevent this from occurring.

If one window is powered by two actuators (typically one on each side), it could easily be damaged if one actuator fails or if they operate at different speeds. If two fixing points are needed (typically on windows more than 1200 mm wide; much less if lightly-framed) then it will often be preferable to use a single actuator with a linkage, for example a rack-and-pinion or a cable drive, or an anti-skew control system.

3.5.5   Reliability of actuators

A typical mean time before failure is 30 000 operations under normal conditions. This represents about five complete operations per day for 250 days per year for a 25-year product life. While at first sight this seems a lot, on several recent buildings it has been found that the controls operated the actuators very frequently, leading to failures after a year or two, or even more rapidly if the motors overheated. It is therefore important that the control system is designed not to move the actuators too often. It is important that a hysteresis loop is integrated into the control.

3.5.6   Linkages and fixings

The fixing of the actuator arm to the window frame is not always straightforward. Window manufacturers will normally require a plate to be bonded to the frame, either by self-tapping screws or adhesive. The number of lever arms required per opening (to lift the window evenly without twisting or racking and to be capable of withstanding wind loads) is usually based on the recommendation of the vent gear suppliers. The European legislation that requires all products to be 'fit for their intended purpose' does not protect the designer, however, and very often problems arise because the windows are either too heavy or too large for the gear installed. (Controls should, of course, normally close vents in high wind speeds).

The protrusion of vent actuator gear into the space makes some gear unsuitable for low-level windows. This has made chain drive and cable drive popular for low-level applications (but only for lightweight windows). Where multiple vents are to be opened in line at high level then rack-and-pinion gear is suitable and sufficiently robust. Very long lever arms sometimes must be curved in order to avoid being obstructed in travel.

Linkages and fixings are as important as any other part of the system but are often taken for granted, making them a common source of failure. Fundamentally, it must be clear:

(*a*)   how the linkage transmits the motion of the actuator to the ventilator without distortion, and

(*b*)   how the actuator and linkages are fixed to the ventilator and the support structure so that the entire assembly is secure and can function satisfactorily through tens of thousands of cycles.

Although the 'one actuator per vent' rule is ideal, it will not always be possible to avoid using multiple linked vents. When these are required, particular care should be taken in specifying the linkage and how it is fixed. Where several windows are driven by a long set of linkages on one shaft or push rod, it can be difficult to get good alignment when they are all driven from one end. It is better to place actuators in the centre if possible.

Having established the loads on the fixings, the method of fixing must be given careful consideration, together with the need for reinforcement of the ventilator and its frame. The fixings, brackets and attachment points should always have a significant safety margin to cope with added shock loads from wind buffeting and actuator operation, and with any rotational and shear forces. As a general rule, fixings with self-tapping screws and rivets will not be adequate: thread-locked screws or bolts are normally required, screwed into threaded fixing plates.

3.6   Control system

3.6.1   Background

The amount of ventilation a building needs, from controlling indoor air quality only in winter to maximum cooling in summer, can easily vary by an order of magnitude. During unoccupied periods even less ventilation may be desirable. The amount of air flowing through a given opening in a given position can also vary widely as the driving forces (wind, natural buoyancy) change with indoor and outdoor conditions. In addition, the internal resistance to cross-ventilation will vary as doors etc. are opened and closed.

With these wide variations in the amounts of air needed and the associated driving forces, it can be difficult to achieve the full range of requirements using the same ventilation device. For example:

—   The large openings required for summer ventilation will need to be shut tight during winter when much less air is required but natural buoyancy pressures are higher.

—   Winter ventilation will require much smaller openings.

—   In summer, people may welcome air movement for its additional cooling effect (provided they can personally decide whether or not to sit in a draught) but in winter people will complain of draughts unless the incoming air is either well-diffused or preheated.

Designers need to develop control strategies very carefully and present them clearly and diagrammatically in a step-by-step manner. Designers are warned against expecting the suppliers of controls and building management

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Example 3.7 Natural ventilation control at Powergen headquarters, Coventry

The automated windows at the top of the atrium at Powergen's mixed-mode headquarters are opened under on/off control as necessary to let heat out of the top and to provide a negative pressure to help draw air in through any open perimeter windows. Occupants can open the middle and lower manually controlled lower windows in the facade to suit their individual requirements, but are asked to shut them when they go home.
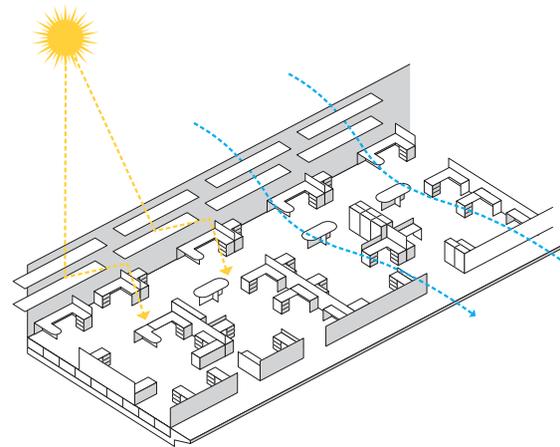
If overnight precooling is required (i.e. evening office temperature is over 23 °C) the automatic controls open the atrium windows and the upper motorised fanlights in the facade to draw air in over the exposed ceilings. The inlets are banked. If the air temperature in any zone falls below 18 °C its bank of windows are closed and reopened if it rises back above 20 °C. All automated windows are closed at an airspeed of 10 m·s⁻¹ in the day and 20 m·s⁻¹ at night.

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systems to provide control strategies based on second-guessing the design intentions.

3.6.2 Flowrates through ventilators

The flow rate through a ventilator is a function of the open area, but often this is not directly proportional to the actuator movement. In particular, the thickness of the ventilator and the way it fits into the building fabric can greatly affect the relationship. With a centre pivot or hinged window, the lower opening can be greatly restricted by the frame, the window cill and the reveal, particularly for the first 100 mm or so of travel. This can provide useful fine control but it may restrict the required opening area for summer ventilation, particularly if safety considerations also restrict the permissible amount of window opening. For centre pivot or bottom-hung hopper windows, the upper opening may also be restricted by the reveal and by any internal blinds. External shading may also restrict flowrates and openings (and may also preheat the outside air, particularly if the shading is dark in colour and of a metallic finish).

3.6.3 Development strategy

A wide variety of control strategies is possible[38] and many will be used in combination. It is necessary to consider how the system will work at all times, not just in normal operation modes but in emergencies such as power failures and fire alarms. The principal purposes are:

— *Localised heat and pollutant removal*: this may be assisted by time-, temperature- or air quality-controlled advanced natural ventilation, particularly via ventilation stacks over heat sources.

— *Indoor air quality and heating*: this is the principal winter control mode. Key control problems are providing sufficient, but not excessive, background ventilation whilst avoiding draughts.

— *Daytime cooling*: key control problems during the heating season include telling whether overheating is a result of insufficient ventilation or too much heating and, in hot weather, determining whether

additional ventilation will necessarily cool the building. (However some people may welcome the air movement even if the air is no cooler.)

— *Night pre-cooling*: strategies are summarised elsewhere[39]. However, previous studies[40,41] suggest that much simpler algorithms are easier to implement and can work better. They include aiming to keep embedded sensors in exposed fabric at a constant temperature and progressively reducing night-time setpoints if daytime temperatures climb. However, care must be taken not to over-cool the building at night in a quest to achieve lower afternoon temperatures or the occupants may object to low morning temperatures.

Natural ventilation may also be part of a mixed-mode strategy where mechanical ventilation or cooling assists the natural systems. Integrated controls are particularly important in such applications[22,38].

3.6.4 Operating natural ventilation openings

Ventilators can be controlled in a number of ways. These include the following (in order of increasing sophistication):

— *On/off*: the opening has two positions, fully open and fully closed. This coarse method is best suited to buffer spaces and atria in which close control of comfort conditions is not essential. It is also more suitable for outlet positions at high level and remote from individual workstations than to inlet positions near workstations, where it may cause draughts.

— *Bank control*: the space has a number of windows or ventilators, in different banks each with on/off control. This allows the ventilation rate to be varied by opening-up banks of ventilators in succession. The banks can be multiple identical ventilators or ventilators of different capacities which can provide either background or rapid ventilation.

— *Stepped control, with each opening having a number of fixed positions*: this simplifies the controller/actuator interface, but does not offer such close control as a modulated system.

— *Fully-modulating operation*: the actuator position is infinitely variable in response to a control signal. This method can potentially give greater control but, in practice, conditions may vary more rapidly than the control and vents are capable of responding. The best strategy is to keep the control algorithms simple. Vent position feedback is still important.

Control may be either 'open loop', where a signal is sent to actuators which are presumed to motor to the required position or 'closed loop', in which the actuator position is monitored and fed back to the control system. Open loop control is widely used because it is cheaper, but case studies[37] have revealed widespread problems with uncertain status and undetected faults. With stepped or modulating operation, positioning errors can also mount up cumulatively in the course of a day.

As a general rule, the further the automated device is from individual occupants, the coarser can be its control. For example, it may be acceptable for opening lights, which let heat out at the top of an atrium, to be under on/off or banked control while control of the inlets will need more finesse. See also Example 3.2 (page 22).

It is also important to recognise that different zones in a building may have different ventilation and/or cooling requirements, and that these requirements may vary with time as the use of the building changes. This means that the development of the ventilation system and the control logic will need to reflect such spatial and temporal variations. As with all aspects of design, there will need to be a compromise between providing ultimate flexibility and the costs of so doing.

3.6.5 Control sensors

The specification, type and location of control sensors can have a major effect on the success of a control strategy. In particular:

— Avoid unrepresentative 'hot spots' when measuring inside and outside temperatures. A common problem is where the sun shines on a sensor or warm exhaust air passes over it.

— Cold spots may also be a problem; for example sensors in the path of incoming outside air or subject to air infiltration through cable entries.

Direct measurement of pollutants (in particular carbon dioxide concentrations) can be effective in controlling air quality but the sensors can be expensive and/or unreliable. Suitable locations for sensors can also be more difficult to find in naturally-ventilated buildings than in common mechanical ventilation extract ducts. An alternative is to use time schedules or occupancy sensors to activate the ventilation.

3.6.6 Combined user and automated control

Naturally ventilated buildings have frequently suffered from insufficient or inappropriate user control. Automatic controls have sometimes also opened windows, only to let in noise, fumes, dust, insects and small animals or switched into draughty night-cooling modes when buildings were still occupied.

Sensible integration of user and automated controls is therefore critical to the success of natural ventilation. The subject is discussed in general terms elsewhere[39,42]. Occupants will always know more about what is going on in their part of the building than will an automated system and therefore must be allowed to make sensible choices.

User behaviour is governed by six key rules:

— If occupants perceive conditions as 'good enough', they will accept them, even if they are not ideal.

— If local conditions are perceived as not good enough, occupants will wish to take action to improve them, e.g. by pressing a button, opening or closing a window, or telephoning a help desk. They will rarely act in anticipation of becoming uncomfortable. The ensuing action also needs to be local; one person may want their window open while their neighbour may not.

— When users decide that they need to intervene, the actions they take will tend be those which they find simplest, most convenient and most accessible. The designer's task is therefore to make the actions that would best suit the design intentions to be simple, speedy and intuitively obvious to the user. For example, if the design strategy requires a high-level window to be operated first, then it should be easier to do this than anything else.

— Rapid response is essential. Occupants who are unable to take action to alleviate their discomfort, or unable to tell whether their actions have had any effect, will become disgruntled.

— If an automated control action (such as window opening) is perceived to be capricious or to make matters worse, occupants will get angry if they find themselves unable to countermand it.

— Users will alleviate discomfort but will rarely re-set controls when the need has passed.

For effective involvement, occupants must be informed about how the building is designed to work, so that the goals of good comfort, air quality and energy efficiency are all achieved. Ideally, the strategy should be clear, straightforward and, as far as possible, intuitive so that people need to be told what to do only once. The control requirement will often change with the context for the user. For example, occupants sitting beside a window are most affected by the draughts from the lower casements while those in the centre of the room are more likely to want to adjust the fanlights.

Suitable combinations of automated and manual control will not only provide backup in the event of BMS malfunctions, but will also empower the occupants, improving their adaptive opportunities[43] and making variations in conditions more acceptable than when there are no override facilities. The automated system must not usurp control too rapidly after user intervention. As a general rule, manual override settings should be retained until the end of the day or at least until there is some major change in internal or external conditions. The ideal system will

operate in the background, allowing users to undertake overrides as they wish, and will afterwards quietly and unobtrusively restore systems to their most appropriate safe, comfortable and efficient default states. Simple, non-technical descriptions of the system are extremely important. Such descriptions are a feature of the log book requirements of Building Regulations Approved Document L2[5]. Guidance on building log books is given in CIBSE TM31[44].

3.6.7 Control schedules

Many control strategies currently use on/off (open/close) control of inlets and particularly outlets. Better control could be obtained where each of the variables are 'scheduled' over a range to determine the maximum travel of the ventilating device. The control should be based on agreed limits of internal temperature (and perhaps relative humidity). External wind speed should influence the control strategy only to maintain safety.

Other criteria, such as outside air temperature, rain intensity, wind speed and wind direction, may be recorded for performance assessment purposes, but are generally not required for the control strategy. Further tuning should be carried out on-site to determine the most appropriate limits for these schedules, based on the dominant factors for the particular site.

3.6.8 Ventilator status indication

As part of an effective strategy, it is important to know, at the point of local control, the status of the ventilator and that control action is being undertaken. Window-type ventilators are often used where they are visible, but even then it is not always easy to tell whether it is tight shut or partially open. In such situations, status lamps or other forms of indication are helpful. Dampers or louvres are frequently hidden from view. In these cases status feedback is particularly important but is rarely included because of cost. Status lamps can also be used to advise users of the system's preferred state. For example, if it is hotter outside (or very cold outside), a red light by the window can advise the occupants that the system would prefer the window not to be opened.

3.7 Installation and commissioning

3.7.1 Installation

The objective is to provide a ventilation system which meets the specified requirements and satisfies the users. This requires properly managed resources to be allocated to the process of constructing a commissionable system. The design project team should be responsible for establishing the commissioning strategy. The system installer must study the strategy and contract documents carefully, so that the strategy and the designer's requirements are fully understood and unresolved items identified so that the commissioning process can proceed.

The development of a commissioning plan, its execution and signing off as being completed satisfactorily is a requirement of Part L2 of the Building Regulations[5]. Commissioning specialists, whether employed by the installer or independently, need to become involved as early as possible, so that their experience can be applied to planning and programming commissioning and pre-commissioning tasks. The installer and commissioning specialist should:

— establish effective lines of communication between them and other parties involved

— review the contract documents to determine the requirements for commissioning, taking nothing for granted and seeking clarification where necessary

— produce a realistic programme with the commissioning activities phased alongside the installation programme

— regularly review the programme during installation to establish the effect of any modifications and delays on the planned static completion and power-on dates, and on any other dates critical to the commissioning activities

— obtain from equipment suppliers and manufacturers their latest information for all items supplied; standard details which are not modified to suit the particular project should always be treated with caution; manufacturers' literature should be checked for installation requirements additional to those specified

— progressively record 'as-installed' information on at least two sets of drawings: one 'clean set', to form the basis for the record drawings and operating and maintenance documentation, and one 'site set' for use by the commissioning specialist

— establish systematic site control procedures to assist the progressive monitoring of the standard of the installation practices maintained on site

— establish an equipment and materials procurement procedure which includes an effective means of checking each delivered item against the specified requirements

— retain all documents and literature provided with each delivered item of equipment for use by the commissioning engineer (and for inclusion in the operating and maintenance manuals).

If the installation is done carefully, commissioning is much quicker and easier, and achieved with greater accuracy. Installers must therefore:

— ensure that their operatives and supervisors are adequately trained

— give appropriate instructions on good housekeeping, workmanship, detailed system arrangements, accessibility and inspection

— ensure that any remedial work has been completed and that all the works comply with the specified requirements before commissioning commences.

During installation, there should be a planned system of continuous inspection and monitoring for correctness, quality and good engineering practice. It can benefit from pro forma sheets which methodically register compliance and monitor the progress of any remedial action. These will help to:

— establish a consistently high standard of workmanship, and maintain it throughout the contract

— stop defects accumulating which need to be put right before proper commissioning can start

— stop defective work being temporarily hidden, only to resurface during commissioning.

3.7.2 Readiness for commissioning: static completion

To be certified as ready for commissioning, an installation must have:

— been installed complete and in accordance with the specification

— been subject to final inspection, with all outstanding remedial works completed

— been successfully tested for air leakage in accordance with the specification and/or relevant HVCA and CIBSE publications[24]

— been satisfactorily cleaned in accordance with the specification

— had all spaces in the vicinity of system equipment and components requiring safe access for commissioning cleared of all obstructions

— been made safe and ready to set to work.

An installation in this state of readiness for commissioning is said to be statically complete.

In general, the commissioning of BMS control systems should be in accordance with BSRIA[45] and CIBSE[46] codes. The commissioning (setting to work) of a BMS-controlled, naturally ventilated building is comparatively straightforward. However, fine tuning (which will need to go on for at least one year after handover) can be more difficult. The initial setpoints for the control system will generally be advised by the designers.

Commissioning and tuning a building's natural ventilation system requires the inlet and outlet vent positions to be manipulated until the system is 'in balance'. This is best indicated when there are no untoward draughts on the occupants under the maximum external wind velocity conditions, no areas of overcooling or overheating, reasonable carbon dioxide concentrations and no perceived air noise. The difficulty in obtaining this condition is that variations in the weather create ever-changing conditions which must be incorporated within the tuning process.

3.7.3 Practical completion

In order to demonstrate successful completion of commissioning, it will be necessary to simulate summer or winter sensor values or to manipulate the setpoints in order to mimic the summer, winter or some intermediate condition. If the requirements of the BMS control system specification can be proved to the consultant in this way, 'practical completion' will be possible.

3.7.4 Fine-tuning after practical completion

It is recommended that the designers' appointments and the contract include provision for fine-tuning in the year following handover. Typically this may require three visits to site in different seasons. How long each visit requires will depend on the size of the building and the complexity of the system; a small building might need only one day each time, while a larger one (say up to 10 000 m^2) might need a week.

On the visits, the contractor should check system operation, focus on any complaints and fine-tuning problems reported by the occupants, and implement changes whilst still on site. The contractor must develop a plan for fine-tuning beforehand. This should include a log book maintained by both the occupant and the contractor in which any reported problems are recorded, with the system status and the inside and outside conditions at the time also being noted. The history built up (which should include details of any changes made to control strategies and setpoints) can be very helpful when considering any control alterations which need to be made.

For fine-tuning to be effective, the controls engineer and the building operator must work together and have confidence in each other, so avoiding situations in which each manipulates the system in a different way. A common direction should be decided, with each party notifying the other of changes made to the system, via the log book.

In innovative buildings (particularly those which combine active and passive systems), contractors, facilities, and maintenance staff may find it difficult to develop mental models of the behaviour of an unfamiliar system and to identify clearly what interventions need to be made. The added perspective of the designer can often assist discussion and lead to more effective resolution of problems. It is therefore recommended that the designers keep in close touch with the fine-tuning activities and plan to attend the site for at least one day in the middle of each fine-tuning visit.

An example of a fine-tuning programme is shown in Table 3.3.

4 Design calculations

4.1 Establishing the required flowrates

The first step in designing a natural ventilation system is to determine the airflow quantities necessary to satisfy the required indoor air quality (IAQ) and thermal comfort criteria. These flowrates will vary for each season of year. The ventilation system must therefore be designed to deliver the required quantity of air to the right places, at the right time.

4.1.1 Ventilation for controlling indoor air quality

Ventilation is needed primarily to satisfy indoor air quality requirements. This requirement is therefore the basis for establishing minimum fresh air rates. The basis for determining an acceptable average ventilation rate is considered in section 2. Any increase in fresh air rate above the minimum necessary for acceptable IAQ will have

— establish a consistently high standard of workmanship, and maintain it throughout the contract

— stop defects accumulating which need to be put right before proper commissioning can start

— stop defective work being temporarily hidden, only to resurface during commissioning.

3.7.2 Readiness for commissioning: static completion

To be certified as ready for commissioning, an installation must have:

— been installed complete and in accordance with the specification

— been subject to final inspection, with all outstanding remedial works completed

— been successfully tested for air leakage in accordance with the specification and/or relevant HVCA and CIBSE publications[24]

— been satisfactorily cleaned in accordance with the specification

— had all spaces in the vicinity of system equipment and components requiring safe access for commissioning cleared of all obstructions

— been made safe and ready to set to work.

An installation in this state of readiness for commissioning is said to be statically complete.

In general, the commissioning of BMS control systems should be in accordance with BSRIA[45] and CIBSE[46] codes. The commissioning (setting to work) of a BMS-controlled, naturally ventilated building is comparatively straightforward. However, fine tuning (which will need to go on for at least one year after handover) can be more difficult. The initial setpoints for the control system will generally be advised by the designers.

Commissioning and tuning a building's natural ventilation system requires the inlet and outlet vent positions to be manipulated until the system is 'in balance'. This is best indicated when there are no untoward draughts on the occupants under the maximum external wind velocity conditions, no areas of overcooling or overheating, reasonable carbon dioxide concentrations and no perceived air noise. The difficulty in obtaining this condition is that variations in the weather create ever-changing conditions which must be incorporated within the tuning process.

3.7.3 Practical completion

In order to demonstrate successful completion of commissioning, it will be necessary to simulate summer or winter sensor values or to manipulate the setpoints in order to mimic the summer, winter or some intermediate condition. If the requirements of the BMS control system specification can be proved to the consultant in this way, 'practical completion' will be possible.

3.7.4 Fine-tuning after practical completion

It is recommended that the designers' appointments and the contract include provision for fine-tuning in the year

following handover. Typically this may require three visits to site in different seasons. How long each visit requires will depend on the size of the building and the complexity of the system; a small building might need only one day each time, while a larger one (say up to 10 000 m²) might need a week.

On the visits, the contractor should check system operation, focus on any complaints and fine-tuning problems reported by the occupants, and implement changes whilst still on site. The contractor must develop a plan for fine-tuning beforehand. This should include a log book maintained by both the occupant and the contractor in which any reported problems are recorded, with the system status and the inside and outside conditions at the time also being noted. The history built up (which should include details of any changes made to control strategies and setpoints) can be very helpful when considering any control alterations which need to be made.

For fine-tuning to be effective, the controls engineer and the building operator must work together and have confidence in each other, so avoiding situations in which each manipulates the system in a different way. A common direction should be decided, with each party notifying the other of changes made to the system, via the log book.

In innovative buildings (particularly those which combine active and passive systems), contractors, facilities, and maintenance staff may find it difficult to develop mental models of the behaviour of an unfamiliar system and to identify clearly what interventions need to be made. The added perspective of the designer can often assist discussion and lead to more effective resolution of problems. It is therefore recommended that the designers keep in close touch with the fine-tuning activities and plan to attend the site for at least one day in the middle of each fine-tuning visit.

An example of a fine-tuning programme is shown in Table 3.3.

4 Design calculations

4.1 Establishing the required flowrates

The first step in designing a natural ventilation system is to determine the airflow quantities necessary to satisfy the required indoor air quality (IAQ) and thermal comfort criteria. These flowrates will vary for each season of year. The ventilation system must therefore be designed to deliver the required quantity of air to the right places, at the right time.

4.1.1 Ventilation for controlling indoor air quality

Ventilation is needed primarily to satisfy indoor air quality requirements. This requirement is therefore the basis for establishing minimum fresh air rates. The basis for determining an acceptable average ventilation rate is considered in section 2. Any increase in fresh air rate above the minimum necessary for acceptable IAQ will have

Table 3.3 Example fine-tuning programme

Visit	Actions to be carried out
First visit	Before fine-tuning can begin, all control points on the system should be checked to ensure that they are working properly. All ventilation devices should be examined to ensure that they close tightly, do not let in rain, and their opening/closing mechanisms are in sound condition and not obstructed. A spot check of the calibration of relevant sensors should be carried out. Trend logging of relevant points should be set up.
	Note: it is often easiest to assess the performance of the system and to identify any important problems if the control strategies are simple to start with, even if this means temporarily disabling some of the more advanced features. Similarly, it can help to start looking at only basic monitored data (though it may well be worth collecting extra data for later analysis)
Second visit	The data from the monitoring set up on the first visit should be analysed. This will give an initial indication of the performance of the system and its controls, and the need for any fine-tuning. Set-points and control algorithms may need adjusting, but take care in making adjustments if there is not enough data to make a firm assessment of the situation.
Third visit	Tuning of other variables should be concentrated upon. For example, is ventilation system working effectively with the current wind speed and direction set-point or is it being limited unnecessarily?
Completion	A report detailing the ventilation system's performance and associated controls should be produced, incorporating information covering the operation of the system, set-points, example graphs and details of changes made. The O&M manual will also need updating to take account of the changes in strategies, schedules and set-points which have been undertaken.

an energy penalty when the space requires heating and an energy benefit when the space requires cooling (except for those periods when external temperatures exceed internal).

In some circumstances it is possible to reduce the design rate by making use of the 'reservoir' effect of the air within the space. This is dealt with in section 4.5.

4.1.2 Ventilation for controlling summer overheating

The estimation of the flows required for summer cooling will be based on a summertime temperature prediction. This will establish the air flows that are needed (day and night) in order to limit the peak temperature in the space to acceptable limits. There are a number of thermal analysis methods available which can be used. Each method has a part to play in the design process. In the following list, each successive method is increasingly flexible in the types of building it can analyse, but increasingly demanding on the user in terms of the input data required.

The methods are:

(*a*) Design charts based on parametric analysis: the BRE's *Environmental Design Manual*[47] is an early example. The user can work only within the range of variables covered by the published design charts.

(*b*) Manual methods included in CIBSE Guide A[6]. Many computerised versions of this type of admittance-based technique are available commercially. The designer can explore a wide range of variables within the constraints of the method. The method is based on a periodic analysis, the predominant period being 24 hours. This can be limiting for buildings with night cooling and thermal mass, where 'coolth' can be stored from one day to another. Another problem is that the ventilation rate is often constrained to be constant for 24 hours, whereas a night cooling strategy implies a high ventilation at night and a reduced rate during the day.

(*c*) Simulation software: these programs, which are based on the numerical solution of equations of heat transfer in buildings, can be used with sequences of real weather data (i.e. not restricted to repeating sinusoidal weather patterns). These programs also tend to provide extra features which may be required when analysing passive buildings (e.g. those with sophisticated shading devices). They are also able to predict the frequency of overheating, rather than just instantaneous peak temperatures, thus giving a better indication of overall comfort. Despite these advantages, it should be stressed that the data input requirements for such models can be demanding and experience is required to obtain reliable results.

Users of all types of model must first satisfy themselves that the chosen technique is appropriate to the particular design task. CIBSE Applications Manual AM11[48] gives guidance in this respect.

4.1.3 Data requirements

To use any of the above techniques, the designer will need to assemble a set of input data covering:

— building description: glazing ratios, orientation etc.

— schedules of internal heat gains (see section 2.1.2)

— weather data (see below)

— ventilation strategy: this will include an understanding of:

(*a*) the intended air flow path, i.e. is fresh air entering the zone at the ambient external temperature, or is the air being transferred from another internal zone?

(*b*) the timing of the ventilation flow (e.g. daytime only, night ventilation, purging with short periods of high ventilation etc.) With natural ventilation, constant ventilation rates are unlikely to exist, even within a single operating period, due to variations in wind speed and inside/outside temperature differences.

Using these input data, the calculation will predict the peak internal temperature. The designer must then adjust the input parameters through an iterative process until satisfactory comfort conditions are achieved, see section 2.1.2. Computer-based methods can be useful in identifying the main heat gain likely to cause overheating

(it may be high solar gain or an internal gain in a particular area). Careful analysis of the results can direct the designer to the key design issues that need to be addressed.

The above analysis will give a picture of the performance of the building under 'design' weather conditions. However, some clients may wish to know how the building will perform throughout the year. This requires multiple analyses using representative weather data for different proportions of the year[25]. For greater accuracy, an hourly dynamic simulation for all 365 days of a representative year can be carried out.

Having obtained a set of parameters that are capable of achieving the comfort conditions required by the brief, the next stage is to size the ventilation openings to generate the required air flow. This stage of the process is discussed in section 4.3.

4.1.4 Weather data

The design of natural ventilation systems uses weather data in two different ways:

— as a means of establishing the required ventilation rates (day and night) that will be required to maintain acceptable thermal comfort

— as a means of establishing the driving forces that will drive the ventilation.

These two uses of weather data are considered below.

4.1.4.1 Weather data for thermal comfort analysis

It is important that the analysis of summer comfort is based on an external climate that is related to an agreed design risk. The different types of model described in section 4.1.2 require different types of data.

The admittance procedure described in section 5 of CIBSE Guide A[6] is based on analysis of a cyclic repeating day. Table 2.19 of Guide A gives maximum daily design temperatures for different degrees of risk, i.e. 2%, 1% and 0.4% exceeded. This would need to be combined with information on the diurnal range to establish the profile of daily temperatures. (Guidance is given in section A5.8 of CIBSE Guide J[25]). Coincident wind speed data can also be established from information in Guide J. One important issue is that maximum overheating may not occur when outside temperatures are highest. If the overheating is primarily driven by solar gain, shading devices that work well in July can be less effective in, say, September when the sun angle is lower.

Simulation programs use weather data sets containing hourly records of the primary weather parameters (dry and wet bulb temperatures, direct and diffuse radiation, wind speed and direction etc.). These data sets can be based on real weather sequences or synthesised data which are processed to represent some form of 'typical' year. The CIBSE recommended weather sets are:

— *Test Reference Year* (TRY): which is a synthesised typical weather year suitable for analysing energy use and overall environmental performance[25].

— *Design Summer Year* (DSY): which is an actual year containing a near-extreme summer, and is the one recommended by CIBSE for use in overheating assessment[49].

Figure 4.1 shows the difference between the TRY and DSY for the three locations. This is given in terms of the frequency with which a given temperature is exceeded during the year for which CIBSE has recommended data sets.

The increased severity of hot weather with latitude is apparent from Figure 4.1. These data are based on an analysis of the 20-year period from 1976 to 1995. It is now accepted that global warming is a reality and estimates of the impact of climate change have been made in terms of a range of possible scenarios[50]. Figure 4.2 shows some examples of the anticipated increase in summer temperatures. (The examples show the range of scenarios but not all individual scenarios.) This likely trend is exacerbated by another aspect of the climate change predictions, namely the increased incidence of very hot days. For example, the frequency with which the temperature exceeds 30 °C is expected to increase by a factor of eight by 2080 for the Medium-High scenario. Coupled with the summer temperature increase is an increase in solar radiation, particularly in the southern parts of the UK. It is predicted that this will be coupled to a reduction in summer cloud cover. This means that the increase in solar radiation will be seen as increased direct beam rather than diffuse radiation. Because of its directionality, beam radiation is easier to control using external shading devices and/or selective location of window position. This adds to the need for improved guidance on solar control measures (see section 2.1.2).
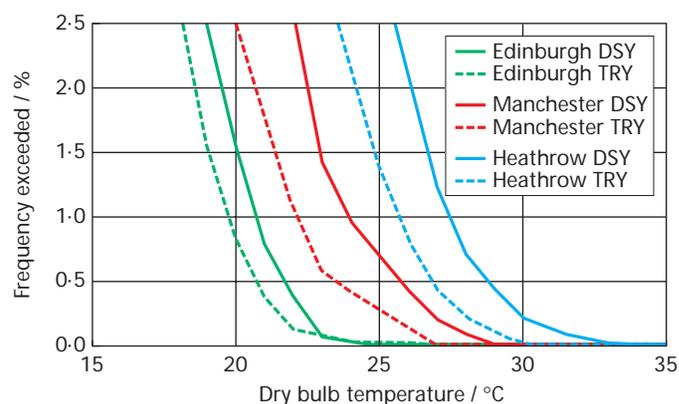
Figure 4.1 Frequency of extreme temperatures for TRY and DSY
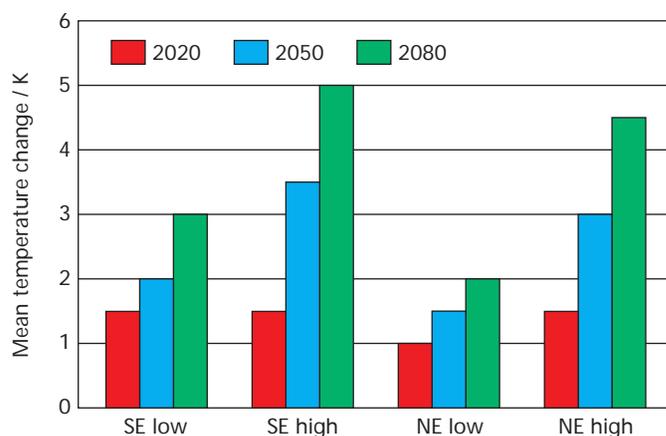
Figure 4.2 Examples of possible increases in mean summer temperature due to global warming

The sizing methods explained in this section are based on steady state calculation methods. It should be appreciated that the purpose of the calculations is to size the openings to deliver the ventilation flows that the thermal analysis has shown to be needed. That ventilation rate is not required 100% of the time. For example, with stack driven mechanisms, as the inside and outside temperatures equalise, the driving pressures will approach zero and, no matter how large the opening, the flows will be very small. However, as shown in Figure 4.3, even if a flow of 5 air changes per hour could be maintained, the cooling effect would be very small once the temperature difference drops below about 3 K.

Consequently, typical practice is to size openings assuming an inside-to-outside air temperature difference of about 3 K in order to set a practical upper limit for the size of the ventilation openings. As the air temperatures equalise, the achievement of comfort is more reliant on radiant cooling from the thermal mass (and by using shading devices to protect from direct solar gain) than on ventilation cooling.

It will be important to test that the design and the control system are able to maintain adequate comfort during typical weather sequences. Simulation models using DSY weather data can then be used to simulate the operating performance of the building and its robustness to user behaviour.

Selecting the wind conditions for sizing openings is a greater challenge than specifying temperatures because it is necessary to specify the wind speed that is used in the definition of wind pressure coefficient. This problem is dealt with in section 4.4.1.

4.2   Selecting a ventilation design tool

Having determined the flowrates that the natural ventilation system will need to deliver, the next stage is to size the components of the ventilation system so that the flows will be delivered. For example, the summer design
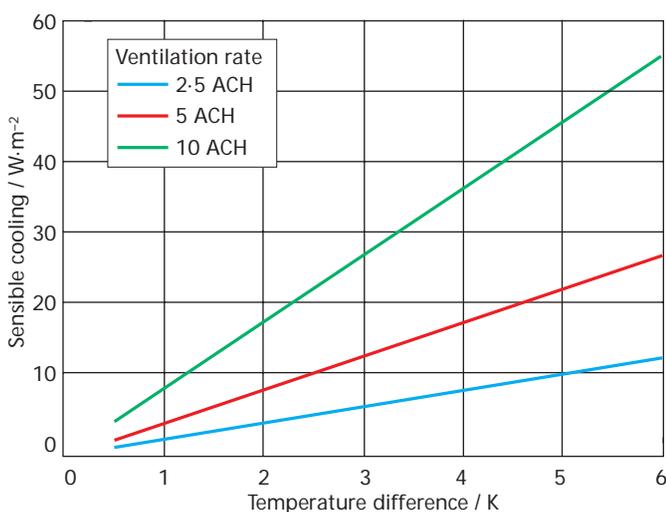
Figure 4.3 Effect of temperature difference and air change rate on sensible cooling capacity of ventilation air (height of space taken as 2.75 m)

condition may determine the maximum sizes of the openings such as windows, whereas the winter design condition may determine the minimum sizes of openings such as trickle ventilators. The control system (manual or automatic) will then need to adjust the opening size between these limits depending on the prevailing ventilation need. Once the initial sizing has been done, the designer may wish to examine off-design conditions and to determine more details of the flows and temperatures inside the building.

There is a range of design tools available, which can be summarised under the following headings:

—   envelope flow models

—   computational fluid dynamics (CFD)

—   combined thermal and ventilation models

—   physical scale models.

The design process is progressive and iterative, different tools being more suited to different stages in the development of the design. Envelope flow models are the simplest tool and are recommended for the initial sizing of openings at the chosen design conditions. The other tools provide more detailed information and are usually more suited to later stages in the design.

The various types of design tool are briefly described below, with guidance on their most suitable range of applications. An extensive description of envelope flow models and physical models, with a comparative discussion of CFD can be found in *Building ventilation theory and measurement*[51]. More detailed descriptions of CFD can be found elsewhere[52,53]. Because of their relevance to the initial stages of design, envelope flow models for single-cell buildings are described in detail in section 4.2.1 and worked examples are presented in section 4.3.

4.2.1   Envelope flow models: single-cell

Envelope flow models solve the equations that govern the flow of air through openings in the envelope of a building. They rely on assumptions about the internal density (temperature) distribution. The basic equations for a single-cell can be illustrated by considering an opening in the envelope.

4.2.1.1   *Basic equations for an opening*

It is common practice to express the relationship between the flow rate through an opening and a pressure difference across it by means of the discharge coefficient and a specified geometric area:

$$q_i = C_{\text{d}i}\, A_i \sqrt{\frac{2|\Delta p_i|}{\rho}} \tag{4.1}$$

where i identifies the opening, q_i is the flow rate through the opening (m³·s⁻¹), $C_{\text{d}\,i}$ is the discharge coefficient (—), A_i is the area of the opening (m³), Δp_i is the pressure difference (Pa) and ρ is the air density (kg·m⁻³).

The discharge coefficient is defined and measured under still-air conditions with uniform density with the flow

being generated by a fan. When the flow is generated by a density difference (i.e. in the absence of any wind effects), it has been shown[51] that the pressure drop in equation 4.1 is given by:

$$\Delta p_i = P_{E0} - P_{I0} - \Delta \rho_0 \, g \, z_i \qquad (4.2)$$

where P_{E0} and P_{I0} are the external and internal hydrostatic pressures respectively at ground level (Pa), $\Delta \rho_0$ is the density difference at ground level (kg·m^{-3}), g is the gravitational force per unit mass (m·s^{-2}) and z_i is the height of opening i above ground level (m).

The density difference is defined by:

$$\Delta \rho_0 = \rho_E - \rho_I \qquad (4.3)$$

where ρ_E and ρ_I are the densities of the external and internal air respectively (kg·m^{-3}).

Equation 4.2 is quite general. It applies to an opening aligned in any direction, irrespective of whether the flow is inward or outward, and whether the inside temperature is higher or lower than the outside temperature. However, it is important to note that the height of the opening, z_i, is the height where the flow leaves the opening, i.e. the height of the outlet. This follows from the outlet boundary condition, namely that the pressure at the outlet is determined by the pressure of the surroundings, and the assumption that the temperature of the air remains unchanged as it flows through the opening. This means that for a long opening in the vertical direction, such as a chimney, z_i will change with the flow direction, see Figure 4.4. For most openings, such as windows and air vents, z_i will not change with flow direction.

If the density of the internal air varies with height equation 4.2 becomes[51]:

$$\Delta p_i = P_{E0} - P_{I0} - \rho_E \, g \, z_i + g \int_0^{z_i} \rho_I \, dz \qquad (4.4)$$

Equation 4.4 allows non-uniform density distributions (as can occur with atria and chimneys, for example) to be dealt with.

4.2.1.2 Effect of wind

When the wind blows the external pressure around the opening is changed by the pressure due the wind, p_{wi},
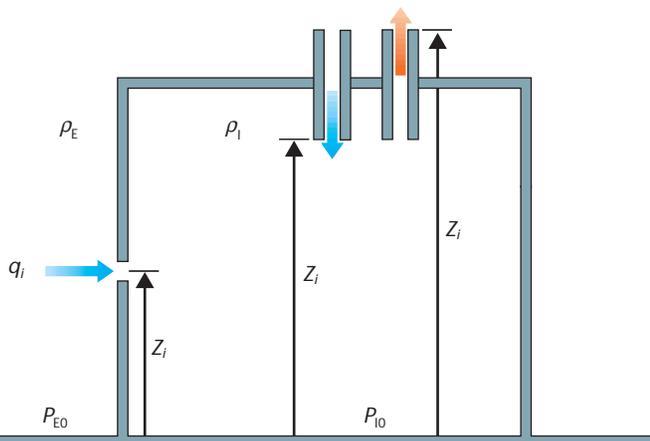
Figure 4.4 Single-cell envelope illustrating definition of z_i

which adds to the hydrostatic pressure and the pressure drop equation becomes[51]:

$$\Delta p_i = P_{E0} - P_{I0} - \Delta \rho_0 \, g \, z_i + p_{wi} \qquad (4.5)$$

where p_{wi} is the pressure of the wind at the point on the envelope at which opening i lies (Pa).

It is common practice to obtain $p_{w,i}$ from wind tunnel tests where wind pressures are quoted in the form of the pressure coefficient:

$$C_{pi} = \frac{p_{wi} - p_{ref}}{0.5 \, \rho \, U^2} \qquad (4.6)$$

where p_{ref} is a reference pressure (Pa) and U is the wind speed (m·s^{-1}).

Thus the pressure difference across an opening whose inlet or outlet is situated in the external flow can be written as:

$$\Delta p_i = P_{E0} - P_{I0} - p_{ref} - \Delta \rho_0 \, g \, z_i + 0.5 \, \rho \, U^2 \, C_{pi} \qquad (4.7)$$

The treatment of wind effect involves several assumptions. For example, the size of the opening is assumed to be small enough for the value of p_{wi} obtained from a point measurement on a wind tunnel model to be appropriate. This is reasonable for small openings such as air vents, but may be less so for open windows. An associated assumption is that the external wind flow around the opening does not affect the discharge coefficient of the opening. This is more reasonable when the outlet of the opening is exposed to the wind (i.e. outward flow from the space) than when the inlet is exposed. None of these assumptions is needed for the treatment of ventilation due to density difference alone and envelope models are more accurate under this condition.

4.1.2.3 Conservation of mass for the envelope

The principle of mass conservation applied to the fixed volume defined by the envelope gives a relationship between the flow rates of the openings:

$$\sum \rho_i \, q_i = 0 \qquad (4.8)$$

i.e. the nett mass flow into the building is equal to zero. In the context of design procedures it is an acceptable approximation to ignore the differences between densities so the equation can be simplified to $\sum q_i = 0$.

4.1.2.4 Solution of the equations

An envelope flow model thus consists of the following three basic equations. For the envelope:

$$\sum q_i = 0 \qquad (4.9)$$

and for each opening:

$$q_i = C_{di} \, A_i \, S_i \sqrt{\frac{2 |\Delta p_i|}{\rho_0}} \qquad (4.10)$$

and:

$$\Delta p_i = \Delta p_0 - \Delta \rho_0 \, g \, z_i + 0.5 \, \rho_0 \, U^2 \, C_{p\,i} \qquad (4.11)$$

Note: in equation 4.10, it is important to include the sign of the pressure difference, which has been introduced into equation 4.10 by the symbol 'S'; the convention used here is that $S = +1$ for flow entering the space and $S = -1$ for flow leaving the space.

Equation 4.11 is the same as equation 4.7 except that $(P_{E0} - P_{I0} - p_{ref})$ has been denoted by Δp_0 for brevity. Although the bracket encloses three terms, it is only the internal pressure P_{I0} that is a variable; P_{E0} and p_{ref} are constant for a given analysis.

For the general case of N openings there are $2\,N+1$ equations. The unknowns are q_i, Δp_i and Δp_0. The equations can be solved by determining the value of Δp_0 at which the continuity equation is satisfied. In physical terms, when the ventilation pattern of a building is changed from one steady state to another (e.g. by opening a window), the internal pressure adjusts until the flows through the openings are such that the continuity equation is again satisfied. Mathematically this adjustment is done by an iterative procedure. When the equations are solved in this way it is referred to as an implicit method.

The equations can be solved directly (i.e. without the need for iteration) by specifying the value of Δp_0 and the values of q_i (magnitude and direction) to find the values of A_i which will give that particular flow pattern. When solved in this way, the model is referred to as an explicit method. This method is particularly useful in the initial design stages for sizing openings, such that the openings give the required flow rates under a specified design condition. Worked examples are given in section 4.3. Using these areas, the implicit procedure can then be used for off-design calculation of flow rates.

The explicit procedure is easy to use for openings with a constant discharge coefficient, i.e. one that does not vary with flow rate (Reynolds number). Most purpose-provided openings fall into this category and manual calculations are not difficult, as illustrated by the worked examples in section 4.3. The explicit procedure is not appropriate for adventitious openings (see section 4.4.4) because such openings cannot be sized in the same way as air vents and windows. Implicit methods are more appropriate for dealing with adventitious openings because the effect of assumptions about the size and distribution of the adventitious leakage can be quickly assessed. However, a means of accounting for adventitious leakage with the explicit method is given in section 4.4.4. Although envelope flow models can account for adventitious openings, this is not feasible with physical models, see section 4.2.7, because of the very small dimensions of the openings at model scale. Nor is it practically feasible with computational fluid dynamics (CFD), because of the need to specify the detailed geometry of a large number of small openings. Most CFD packages will allow special inlet and outlet flows to be specified as boundary conditions and adventitious openings could be dealt with in this way.

Envelope flow models are best suited for dealing with openings with unidirectional flow. For large openings such as windows it is possible for bi-directional flow to

occur and this is more difficult to treat, although there are ways of doing so[51].

4.2.2 Multi-cell envelope flow models

Multi-cell envelope flow models are the general case of single-cell envelope flow models. They include the effect of the internal partitions, not only in the sense that partitions can increase the resistance to flow through the building, but also in the sense that they allow temperature differences between rooms to be defined. The equations that are solved and the assumptions that are made are in most respects the same as for single-cell models. Zonal models are a step further than multi-cell models in that the rooms are further divided into a number of zones. They do not offer any real benefits to the design of natural ventilation, unless they form part of a combined thermal and flow model.

4.2.3 Unsteady envelope flow models

There are more advanced envelope models that can account for the variation of external wind pressures with time due to wind turbulence. They predict the instantaneous flow rates when the external pressure fluctuations are specified. Under most circumstances the errors in ventilation rates arising from a neglect of unsteady effects will be small and can be neglected[54]. However, unsteady envelope models can be useful in the design of ventilation chimneys in order to avoid flow reversal.

4.2.4 Non-dimensional graphs

When results of theoretical calculations or experimental measurements are expressed in non-dimensional form, they can have much wider application. Wind tunnel data are often presented in this form, because a small number of tests at one condition can then be applied to many other conditions. One example of this is the use of the pressure coefficient, which can be used for any wind speed.

Although not strictly a distinct design method, graphs generated from envelope flow models allow quick calculations to be made[54] and may be useful at any stage of a design to give a quick estimate of proposed changes. Worked examples are given in sections 4.3.5 and 4.4.4.

4.2.5 Computational fluid dynamics (CFD)

Whereas envelope flow models solve the equations of motion for the bulk flow through openings, CFD solves the fundamental equations of motion for individual elements of fluid at all points in the specified space. Of all the design tools, it is unique in the sense that it predicts the air motion at all points in the flow. By including thermal equations, CFD also predicts the effects of buoyancy and the temperature field. CFD can address questions such as stratification and local air movement. Therefore the method is particularly applicable to large spaces such as atria, although such flows may be inherently unsteady and the use of a steady CFD solution may not be realistic. Because the computations are extensive, CFD is more suited to generate 'snapshots' of how the design would work at a given moment, rather than for the initial sizing of openings.

The applications of CFD to the design of naturally venti-lated buildings include:

(*a*)   calculation of velocity and temperature fields in rooms and single-cell buildings

(*b*)   calculation of velocity and temperature fields in multi-cell buildings

(*c*)   calculation of surface wind pressure distributions on buildings

(*d*)   whole-field calculations, i.e. the combination of (*a*) and (*c*)

(*e*)   calculation of flow through components, e.g. discharge coefficients of chimneys.

The first application is now quite common. Figure 4.5 is an example that illustrates the use of CFD to air temperature in a building with top-down ventilation[55]. CFD is generally used for more complicated cases but this example has been chosen because it can be compared directly with the results of the saltbath technique shown in Figure 4.7 (page 44).

Commercial CFD software is widely available. Most soft-ware packages consist of three distinct parts:

—   *Pre-processor*: where the user sets the boundary conditions for the solution, including the specifi-cation of the computation grid and the number of cells. The number of cells is likely to be of order 10 000 for simple cases such as a small room and of order 1 000 000 for large buildings.

—   *Solver*: which carries out the numerical solution. This is an iterative procedure, which continues until convergence is obtained, i.e. a stable solution is reached with error terms below pre-defined limits. Solution times can vary from a few hours to several days, depending on the complexity of the boundary conditions, the number of cells and the capacity of the computer. The onus is on the user to assess whether convergence has been satis-factorily achieved. This is not necessarily straightforward, partly because the criteria used by the software may not relate to the part of the flow that is of interest and partly because instabilities can occur.

—   *Post-processor*: where the results are presented in a suitable form. Since the solution generates vast amounts of data it is important to be able to

Figure 4.5 Example of CFD results for air temperature; cool air enters through the chimneys and leaves through the atrium

present it in a meaningful way. One common form of output is the contour plot where parameters such as velocity and temperature that lie in certain ranges are identified by different coloured areas. This type of flow visualisation can be helpful for presentations to clients.

It is important to appreciate that the solution obtained will depend to a greater or lesser extent on the following parameters:

—   *Boundary conditions*: specifying the boundary conditions for a calculation is not a trivial matter. Even for a relatively simple case of a single room with wind alone, the velocity conditions at each opening need to be specified, which is not always easy or obvious. If heating or cooling is involved, the thermal boundary conditions at the surfaces of the room must also be specified and this is even more difficult. Inevitably there will be uncertain-ties in specifying boundary conditions and this will be reflected in uncertainties in the CFD results. The sensitivity of the results to the conditions may be determined by carrying out specimen calcula-tions. Although software packages include advice on specifying boundary conditions, the user needs experience of the conditions that occur in practice. It is possible to specify boundary conditions for which there is no converged solution or for which the solution is unstable; such problems are more likely when buoyancy effects are significant[56].

It is normal practice to carry out steady calcula-tions, i.e. the boundary conditions do not vary with time, and it is implicitly assumed that the calculation will converge to the correct steady state solution. This assumption is not necessarily valid because with complicated flows involving buoy-ancy there may be more than one steady solution. In principle it is better to carry out an unsteady calculation in which the full flow field is specified at time $t = 0$ (i.e. the initial values of velocities etc. at all points) and the remaining boundary con-ditions are specified as functions of time. Such calculations are extremely demanding and are rarely carried out. Nevertheless, when looking at the fine detail of a steady solution it should be remembered that such a solution may well be a simplification of reality.

—   *Calculation grid*: most software packages reduce the amount of effort required to generate an appro-priate calculation grid. However, with complicated and/or large building geometries, skill is required to obtain a grid that minimises computation time and gives the required precision in the areas of interest. Clearly the results should be independent of the chosen grid and the number of cells and as a general rule this should always be checked. Examples of the problems of convergence, grid dependency and stability that can arise with CFD are discussed elsewhere[57]. It should be noted that envelope flow models can also suffer from conver-gence problems, due to inappropriate numerical convergence criteria, the existence of more than one solution to the equations or to the presence of very large openings with very small pressure differences.

— *Assumptions inherent in the equations*: although CFD solves fundamental equations, it still relies on assumptions and approximations. The main ones relate to the properties of turbulence and to heat transfer, particularly close to surfaces. Commercial CFD codes usually offer a range of turbulence models and the user can investigate the effect of changing the model. Turbulence models are still the subject of considerable research and development. For example, it is now generally recognised that the large eddy simulation (LES) model is better than others for predicting pressure distributions on simple buildings, because it gives better prediction of flow separation. However the calculation of wind pressures on complex arrangements of buildings that are routinely measured in wind tunnels is a major challenge and the use of CFD as a virtual wind tunnel is still open to question.

If CFD is used purely for qualitative flow visualisation (e.g. demonstrating flow patterns to clients), the uncertainties associated with boundary conditions, grid size and turbulence model are probably not important, provided convergence is obtained and the results are not grid dependent. However, if quantitative results are important (e.g. meeting certain temperature requirements), the inexperienced user may well be advised to consult experienced users. This is particularly true when buoyancy and heat transfer effects are included, since the uncertainties are more likely to be significant.

4.2.6   Combined thermal and airflow models

One of the difficulties in designing natural ventilation systems is the estimation of internal temperature distribution. Especially in summer conditions, the temperature of each space will depend on the ventilation rate, which will itself depend on the temperature distribution, particularly when using buoyancy-driven strategies.

In principle this difficulty can be overcome by combining a ventilation model (envelope flow or CFD) with a thermal model. Ideally the two models would be completely integrated such that the governing equations are solved simultaneously. A simpler strategy is to solve the two models separately, with some form of link between their solutions. Examples of this strategy and the sort of problems that can arise can be found elsewhere[56,58,59].

There is a class of relatively simple model that combines an envelope flow model with the internal flow associated with buoyant plumes, leading to simultaneous prediction of ventilation rate and temperature stratification within the space. Although capable of giving good quantitative agreement with simple physical models, the assumptions made about the internal air motion and heat transfer mean that this type of model is not at present suitable for quantitative design.

4.2.7   Physical models

Although the majority of ventilation design is carried out using mathematical models, there is a place for physical models.

Figure 4.6 Environmental wind tunnel with building model

4.2.7.1   Wind tunnel testing

Environmental wind tunnels, such as that shown in Figure 4.6, are the main source of information on wind pressure coefficients, see section 4.4. The results of measurements are available as design data for generic building forms; alternatively, bespoke measurements can be made for individual building designs. Bespoke measurements may be required even for simple building shapes if there are specific local obstructions (e.g. a nearby high-rise building) or an unusual site layout.

Wind tunnels can also be used for measuring directly the ventilation rate of a building, subject to certain limitations on the size of the building and the openings. The building needs to be large enough such that the volume of the envelope at a model scale of, say, 1/100 allows a tracer gas measurement inside the model. Similarly the full-scale openings need to be large enough for them to be accurately modelled. For example, an open window can be adequately modelled at 1/100 scale, but a domestic air vent may not be (due to dependence on Reynolds number causing errors in applying the results to full-scale). However, if the requirements can be met, wind tunnel testing offers relatively high accuracy in the determination of ventilation rates due to wind because the effects of wind turbulence are inherent in the measurements. It is also possible to determine ventilation rates under the combined effect of wind and buoyancy. Simple scaling laws can be applied to calculate the full-scale ventilation rate[54].

Wind tunnel testing can also be used to optimise the performance of specific ventilation openings, such as chimneys or wind towers. This may take the form of simply measuring wind pressures at the outlet of the openings to ensure that they are negative. It is now possible to measure instantaneous flow rates in model chimneys and thereby determine directly how susceptible the chimney is to flow reversal[60].

4.2.7.2   Modelling with liquids

The simulation of air motion in rooms with liquids has been employed in research for many years. The direct approach of using heated water is relatively simple in practical terms but, as with all scale modelling techniques, the conversion of model results to full-scale conditions
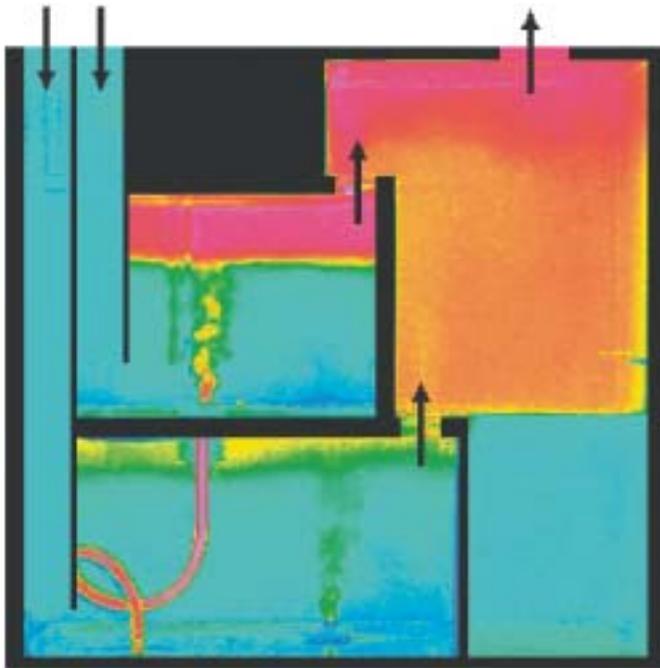
Figure 4.7 Example of a saltbath test; corresponding CFD results are shown in Figure 4.5

can be difficult. The saltbath method[61] is a relatively recent development and is primarily used for testing buoyancy-driven ventilation strategies. A small scale model of the envelope is immersed in a transparent bath containing saline solutions of different concentrations that simulate the temperature (density) differences.

The technique is useful for giving the non-technical members of the client and design teams a good visualisation of airflow behaviour. The flows can be visualised either by direct dye injection or by shining light through the transparent model, the variation in the refractive index of different salt concentrations causing shadows to be cast on a translucent screen. Quantitative estimates of the specific temperature distribution can be made by measuring the solution concentration using a conductivity probe. However it should be noted that heat transfer boundary conditions at surfaces are not completely simulated, and therefore local effects, such as solar patching on the floor of an atrium, cannot be dealt with. Figure 4.7 shows top-down ventilation in a two-storey building connected to an atrium[61]. The blue regions indicate regions of cool air and the orange and red regions indicate where the warm air gathers in the space.

4.2.8   Application of tools

Table 4.1 gives a broad indication of where each design tool might be used in the various stages of a project.

4.3   Design procedures using envelope flow models

It is assumed that the basic configuration of the building and the intended flow strategy have been agreed (see section 2.2). In particular, it is assumed that the required flow rates through openings have been quantified (in magnitude and direction) under specific wind and temperature conditions. The next stage is to size the components of the ventilation system so that the flows will be delivered. Procedures for the initial sizing of openings based on explicit envelope flow models are illustrated below. This is done for a summer condition, but exactly the same procedures can be applied to winter conditions. Before carrying out the calculations there are several preliminary steps:

—   *Step 1: identify isolated rooms and spaces*: these are rooms that can be considered to be isolated from other parts of the building (in terms of their ventilation) and can therefore be treated by very simple explicit envelope flow models. To fall within this category the openings in the internal part of the envelope need to be much smaller than the openings in the external part of the envelope. This can often be the case for the summer design condition, but it is less likely to be valid in winter. Nevertheless the designer may wish to size the openings on this basis for both design conditions. The two basic cases are single-sided ventilation and crossflow ventilation, as described in section 4.3.1.

—   *Step 2: determine which parts of the building can be treated as a single space (i.e. a single cell)*: in a single cell all the rooms are connected by openings that are much larger than the openings in the external envelope. With such buildings it is necessary to consider all openings simultaneously when sizing them. This can be done with explicit single-cell envelope flow models, as described in section 4.3.2. If the building falls into the category where internal openings are neither very large nor very small in relation to the external openings, it may

Table 4.1 Uses of design tools

Project stage	Tool	Comments
Initial concept	Explicit envelope flow models	Use for initial sizing of openings at design conditions
Optimisation	Implicit envelope flow models, single and/or multi-cell	Use for looking at off-design conditions to test the robustness of the design
Detailed analysis of 'special' spaces and components	Computational fluid dynamics (CFD)	Use for determining details of velocities, temperatures and comfort parameters inside the space
	Saltbath	Use where stratification is a particular issue
	Wind tunnel	Use where wind effects are important, e.g. for siting of stack outlets
Performance assessment	Linked thermal and flow models	Use for overall seasonal/annual performance assessments
Data generation	Wind tunnel	Use for determining pressure coefficients
	Computational fluid dynamics (CFD)	Use for determining pressure coefficients Use for determining discharge coefficients

be desirable to make use of multi-cell implicit envelope flow models. However, in practice it would be simpler to size the openings using an explicit model and then use an implicit model to check the effect of the internal openings. Alternatively, the openings could be sized for the two cases (single-cell and isolated spaces) and the larger values chosen (assuming that the building will operate in both modes).

— *Step 3: specify the input data required to obtain a solution*: this will include the positions of the openings, their discharge coefficients and the relevant wind and temperature conditions (see section 4.4).

— *Step 4: size the openings*: using the relevant procedure (see sections 4.3.1, 4.3.2, 4.3.3 and 4.3.4).

— *Step 5: check practicality of the sizes of openings*: checks should include:

(*a*)   What proportion of each facade does the opening represent? In the winter design case, the Building Regulations recommend certain minimum areas of trickle ventilator. Depending on the design of the building, the proposed area may be greater or less than the recommended value. If the proposed area of trickle ventilation is less, the designer will need to demonstrate that the required air flows can be delivered, possibly by taking account of adventitious openings.

(*b*)   What is the velocity of the air through the opening and the implication for draughts?

(*c*)   How sensitive is the design to operational misuse? (For example, if internal doors are shut in a cross flow design, are transfer grilles necessary?)

If checks such as these identify shortcomings in the design, revised parameters must be substituted in the equations and the viability of the amended design reassessed.

4.3.1   Isolated rooms and spaces

A simple example of a building with isolated spaces and rooms is shown in Figure 4.8. On the ground floor, the rooms are isolated and separated by a corridor. The upper two floors are open plan, but isolated from each other.
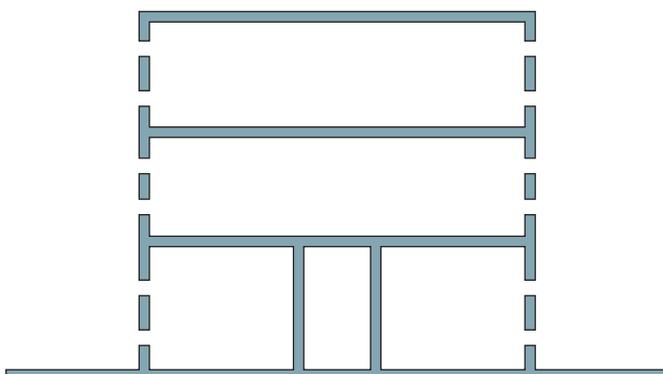
Figure 4.8 Illustration of isolated rooms and spaces

Four common cases are shown below with the appropriate equations for sizing the areas. Cases 1, 2 and 3 are examples of single-sided ventilation. The ground floor rooms in the building shown in Figure 4.8 rely purely on this form of ventilation. Case 4 is an example of crossflow ventilation. The two upper floors rely on this form of ventilation when wind is dominant but on what is basically single-sided ventilation when buoyancy is dominant (i.e. case 1 or 2 applied to each wall). Cases 1 and 4 are simple examples of envelope flow models. Cases 2 and 3 rely more on empirical data.

Case 1: Single-sided, two vents, buoyancy driven

This case represents single-sided ventilation through two identical vents driven by buoyancy alone, see Figure 4.9.

The area A of each opening required to give a ventilation rate q for a specified value of h is:

$$A = \frac{q}{C_d} \sqrt{\frac{(T_I + 273)}{\Delta T\, g\, h}} \qquad (4.12)$$

where A is the area of each opening (m²), q is the ventilation rate (m³·s⁻¹), C_d is the discharge coefficient, T_I is the internal temperature (°C), ΔT is the difference between the internal and external air temperatures (K), g is the gravitational force per unit mass (m·s⁻²) and h is the height between the openings (m).

A typical value for C_d is 0.6.
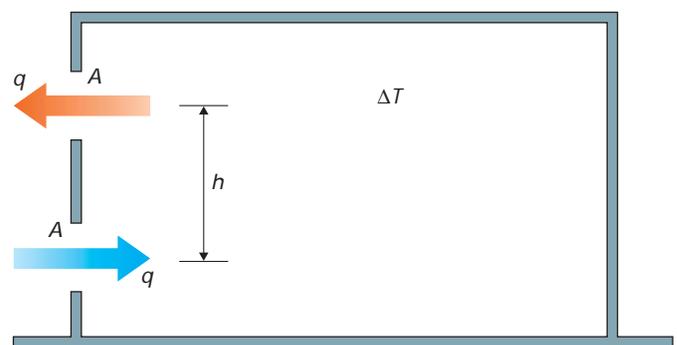
Figure 4.9 Case 1: single-sided ventilation, two identical openings, driven by buoyancy alone

Case 2: Single-sided, single vent, buoyancy driven

This case represents single-sided ventilation through an open window driven by buoyancy alone see Figure 4.10.
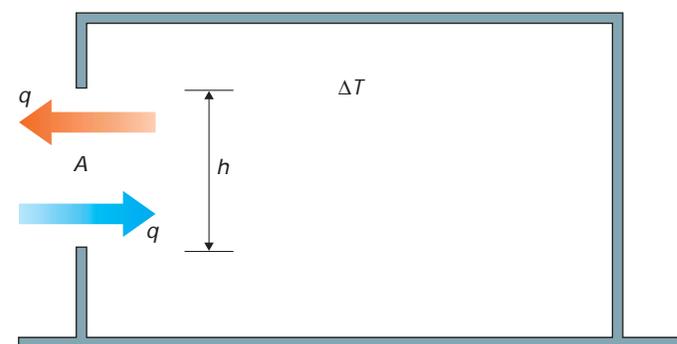
Figure 4.10 Case 2: single-sided ventilation, single opening, driven by buoyancy alone

The area required to give a ventilation rate through a single opening of area A is again given by equation 4.12 but in this case h is the height of the single opening rather than the distance between openings.

Case 2 is basically the same as case 1, but the value of C_d is typically 0.25. This is lower than the value in case 1 partly because only half the area A is available for air entry.

Case 3: Single-sided, single vent, wind driven

Case 3 represents single-sided ventilation through an open window, driven by wind alone see Figure 4.11.

Figure 4.11 Case 3: single-sided ventilation, single opening, driven by wind alone

The area required to give a ventilation rate for a specified value of wind speed is:

$$A = q / C\,U \qquad (4.13)$$

where U is the wind speed (m·s^{-1}).

The value of the coefficient C depends on (*a*) the geometry of the opening, (*b*) the position at which the reference wind speed is measured and (*c*) the flow field around the building. Reported values range from about 0.01 to 0.05 when U is measured at the same height as the building[51]. The value is low because the air entry arises as a result of turbulent diffusion.

Case 4: Crossflow ventilation, wind driven

In this case, ventilation is by wind alone see Figure 4.12.

The ventilation area required to give a ventilation rate q for a specified value of ΔC_p is given by:
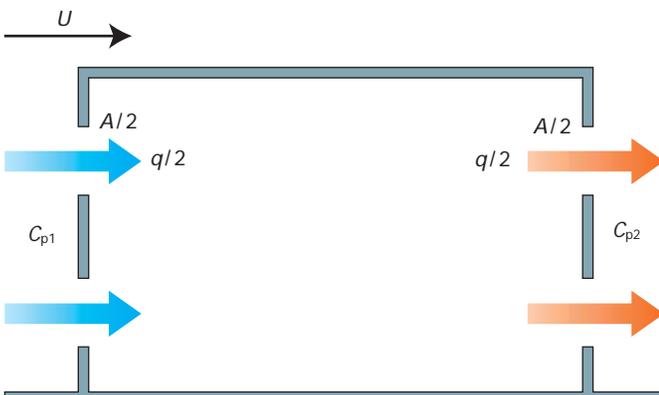
Figure 4.12 Case 4: crossflow ventilation driven by wind alone

$$A = q \left(C_d\, U\, \sqrt{\frac{\Delta C_p}{2}} \right)^{-1} \qquad (4.14)$$

where A is the total ventilation area (each wall) (m^2) and ΔC_p is the difference between the wind pressure coefficients C_{p1} and C_{p2}.

Note: in cases 1 and 4 it is assumed that the openings are identical; different equations will apply if the openings have different areas or discharge coefficients (see the examples in CIBSE Guide A[6] and BS 5925[62]).

4.3.2   Single-cell buildings, uniform temperature

Examples of single-cell buildings are given in Figure 4.13. In case 5, the spaces are all connected to an atrium, the aim being to induce fresh air into all of the occupied spaces with all stale air passing out through the upper outlet. The aim is the same for case 6, but the spaces are connected to a large stack. As far as the explicit model is concerned they can be treated in the same way.

Case 7 is similar to case 6, but here the space is connected to a well-defined chimney. The difference between cases 6 and 7 is that the stack in case 6 is wide open to the occupied spaces. Thus the temperatures within the stack and the space will tend to be the same at any given height. Also the resistance to flow of the stack can be neglected relative to the resistance of the outlet. In case 7 the chimney is closed to the surroundings, except at the inlet, and has narrow dimensions. This means that the temperature within the stack can be considerably different to that in the room (e.g. solar-powered chimney). The chimney will support density differences in the horizontal direction, but the stack will not. It also means that the whole chimney must be considered when evaluating its discharge coefficient.

Case 8 is an example of a space ventilated by two combined chimneys. For any given wind direction, one acts as an air inlet and one as an air outlet.

Worked examples using the explicit method for cases 6, 7 and 8 are given below. (The procedure for case 5 is exactly the same as for case 6.) It is initially assumed that the temperature is uniform throughout the building. The relevant properties of the building are given for each example. The calculations can be carried out by hand but they are ideally suited to a spreadsheet*.

Note: the results of the calculations are presented here to a precision of four or five significant figures. This is done to allow the user to check their calculations. For an actual design, there is little justification for calculating the open areas to more than two significant figures. For the worked examples given here, the density differences $\Delta\rho_0$ and $\Delta\rho_c$ have been evaluated using equations 4.33 and 4.34. To reproduce the present results it is necessary to use the same equation although, as noted in 4.4.2, the equations are approximate.

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* A suitable spreadsheet may be downloaded from the CIBSE website (www.cibse.org/venttool)
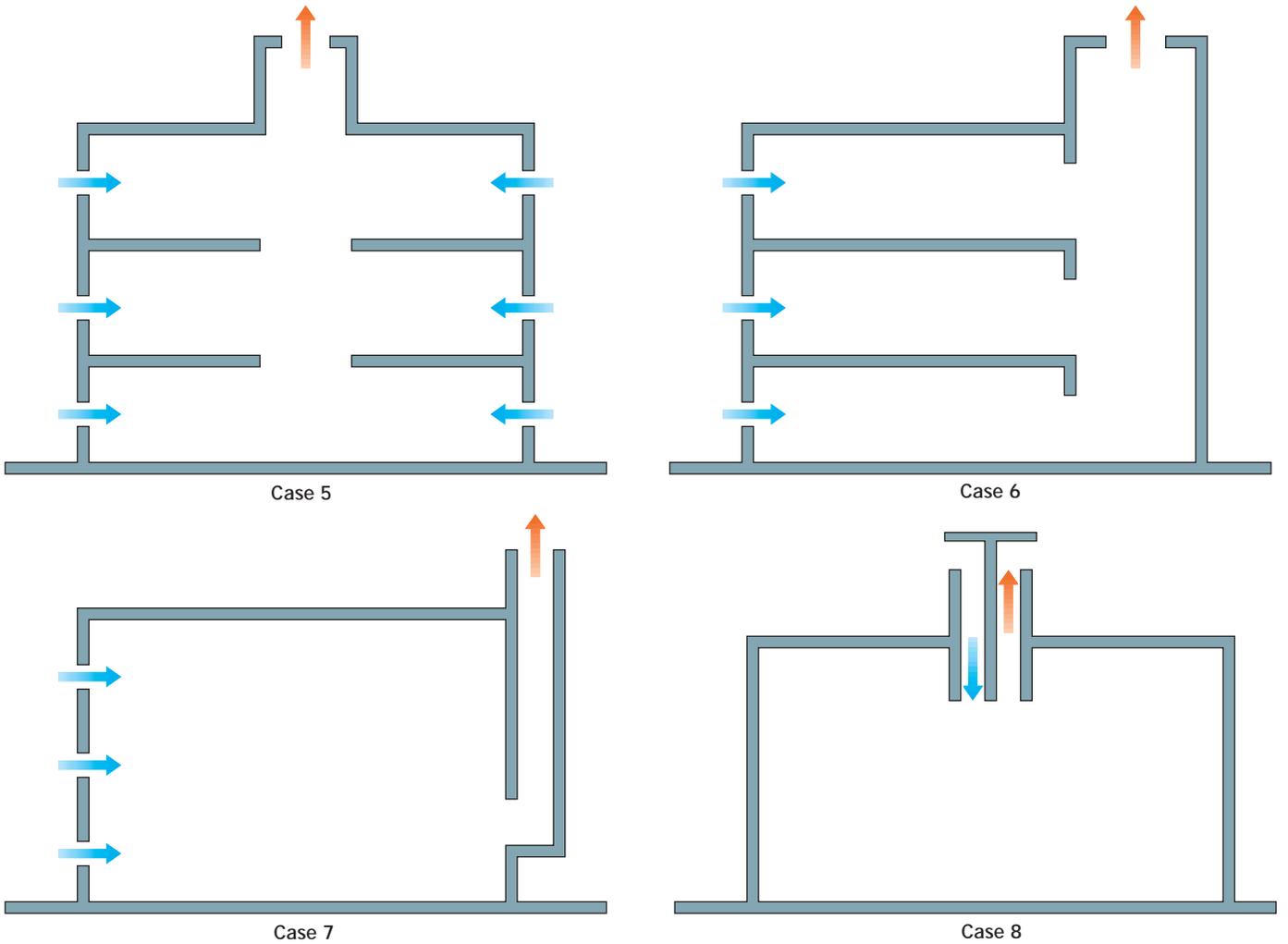
Figure 4.13 Examples of single-cell buildings

To use the explicit method it is necessary to specify a value for Δp_0. The value must be compatible with the flow pattern specified for the design but there is still some flexibility in the value. Guidance on specifying a value for Δp_0 is given in Examples 4.1 to 4.4.

Example 4.1: case 6: buoyancy alone (uniform internal temperature)

The aim is to achieve the flow pattern shown in Figure 4.14, i.e. fresh air enters all rooms and all of the stale air exits through the upper opening. This flow pattern means that the pressure difference must change sign at a height which lies somewhere between z_3 and z_4. The height at which $\Delta p_0 = 0$ is known as the 'neutral height', z_n. By specifying z_n, Δp_0 is specified by equation 4.11 (with wind terms omitted, i.e. wind speed set to zero) by putting $\Delta p_i = 0$ and $z_i = z_n$, i.e:

$$\Delta p_0 = \Delta \rho_0\, g\, z_n \qquad (4.15)$$

It then follows that Δp_i is known and is given by:

$$\Delta p_i = \Delta \rho_0\, g\, z_n - \Delta \rho_0\, g\, z_i \qquad (4.16)$$

The required areas can then be found using a rearrangement of equation 4.10, i.e:

$$C_{\mathrm{d}i}\, A_i = \frac{q_i}{S_i} \sqrt{\frac{\rho_0}{2|\Delta p_i|}} \qquad (4.17)$$

Note that the equations are solved for the product $C_{\mathrm{d}i}\, A_i$. There is no need to carry out separate calculations when either $C_{\mathrm{d}i}$ or A_i is changed, provided the product remains the same.

Table 4.2 shows the calculations for a summer design condition with $\Delta T_0 = 3$ K and with the neutral height specified as being at the top of the occupied spaces, i.e. $z_n = 10$ m.

The value of Δp_0 is first calculated from the known internal and external conditions, as follows:

— external temperature: $T_E = 25\ °C$

— internal temperature: $T_I = 28\ °C$

— temperature difference: $\Delta T_0 = 3$ K

— wind speed: $U = 0\ \mathrm{m\cdot s^{-1}}$

— dynamic pressure: $0.5\, \rho\, U^2 = 0$ Pa

— reference density: $\rho_0 = 1.2\ \mathrm{kg\cdot m^{-3}}$

— density difference (eqn. 4.33): $\Delta \rho_0 = 0.01208\ \mathrm{kg\cdot m^{-3}}$.

The pressure difference is then obtained from equation 4.15, thus:

$$\Delta p_0 = 1.851\ \mathrm{Pa}$$

Equations 4.16 and 4.17 are then used to determine Δp_i and $C_{\mathrm{d}i}\, A_i$. The results are given in Table 4.2.

U

$z_4 = 11.5$ m

$T_E = 25\ ^\circ C$

$z_3 = 8.35$ m $q_3 = 0.448$ m³·s⁻¹

$z_2 = 5.1$ m $q_2 = 0.448$ m³·s⁻¹ $T_I = 28\ ^\circ C$

10 m

$z_1 = 1.85$ m $q_1 = 0.448$ m³·s⁻¹
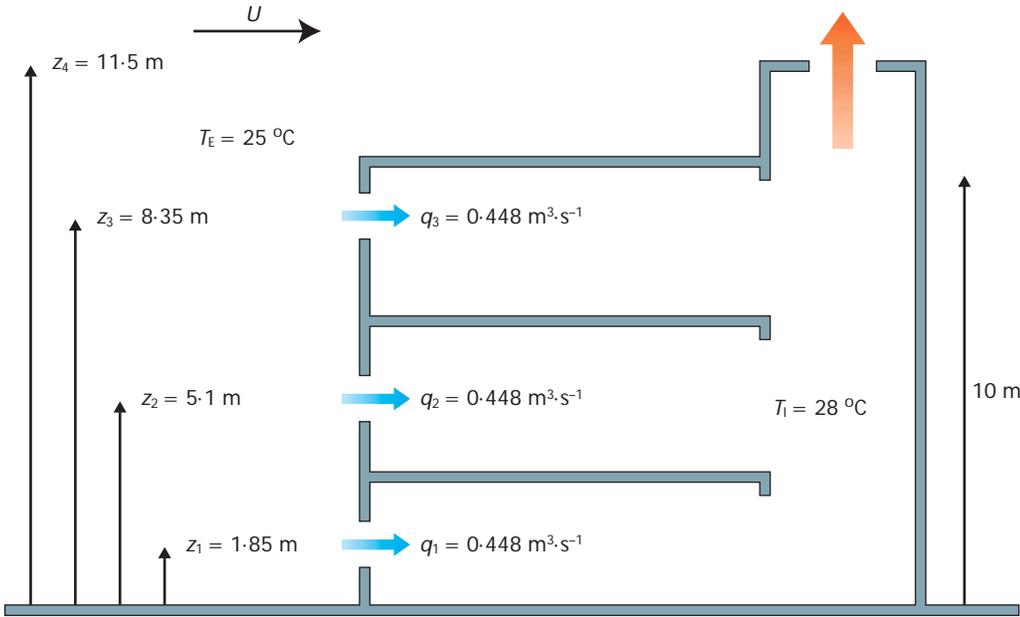
Figure 4.14 Examples 4.1, 4.2, 4.3 and 4.4: properties of building for case 6

Table 4.2 Example 4.1: opening areas — buoyancy alone, uniform temperature

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	—	0.448	Inward	+1	0.9659	0.3531	0.61	0.579
2	5.1	—	0.448	Inward	+1	0.5807	0.4554	0.61	0.747
3	8.35	—	0.448	Inward	+1	0.1955	0.7848	0.61	1.286
4 (outlet)	11.5	—	−1.344	Outward	−1	−0.1778	2.4692	0.61	4.048

Table 4.3 Example 4.1: opening areas — buoyancy alone, alternative specification of $\Delta\rho_0$

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	—	0.448	Inward	+1	0.9570	0.3547	0.61	0.582
2	5.1	—	0.448	Inward	+1	0.5718	0.4589	0.61	0.752
3	8.35	—	0.448	Inward	+1	0.1867	0.8032	0.61	1.317
4 (outlet)	11.5	—	−1.344	Outward	−1	−0.1867	2.4097	0.61	3.950

Table 4.4 Example 4.1: opening areas — buoyancy alone, flow pattern reversed

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	—	−0.448	Outward	−1	−0.9562	0.3549	0.61	0.582
2	5.1	—	−0.448	Outward	−1	−0.5749	0.4577	0.61	0.750
3	8.35	—	−0.448	Outward	−1	−0.1936	0.7887	0.61	1.293
4 (outlet)	11.5	—	1.344	Inward	+1	0.1760	2.4816	0.61	4.068

Although using any value of z_n between 8.35 and 11.5 m would satisfy the flow pattern, it is important to note that a value close to one of these two extremes will lead to a very large area, which is unrealistic. An alternative way of specifying Δp_0 is to set the values of Δp_i for openings 3 and 4 as opposite and equal. This leads to $\Delta p_0 = 1.1762$ Pa and the resulting calculations are shown in Table 4.3. It will be seen that the calculated areas do not differ greatly from those in Table 4.2.

Specifying Δp_0 completely determines all the values of Δp_i. It follows that the height of any opening can be changed without affecting the results for other openings. Also, the flow rate through any of the *inlet* openings can be changed

without affecting any of the other *inlet* areas. The area of the outlet opening will change because the outlet flow rate changes when any inlet flow rate changes. In reality, changing an inlet area will lead to changes in the neutral height and the flow rates through all of the openings. This is what is predicted by an implicit method and this demonstrates the basic difference between the explicit and implicit methods.

With uniform temperature the flow pattern in Figure 4.14 is achievable only when the internal temperature is greater than the external temperature. The building may actually be designed to make use of night ventilation with the aim of keeping the internal temperature below the external

temperature at all times. Although it is mathematically possible to obtain a solution, it will lead to the sign of Δp_i being opposite to the sign of q_i, which is physically impossible. However, it is possible to achieve the required flow pattern when the internal temperature is less than the external temperature for cases where the density is not uniform, i.e. where internal stratification occurs (see Example 4.4, below) and for the case with a chimney (see section 4.3.3, Example 4.6).

To investigate the case where the internal temperature is less than the external temperature and the flow pattern in Figure 4.14 is reversed (as can occur as a result of night cooling or downdraught cooling), it is necessary to reverse the signs of q_i and S_i. Thus, reversing these signs and putting $T_I = 25$ °C, $T_E = 28$ °C and $\Delta T_0 = -3$ K in Example 4.1, the results shown in Table 4.4 are obtained. *Note*: the small differences in the magnitudes of the areas compared to those given in Table 4.2 are simply due to the manner in which $\Delta \rho_0$ is defined.

Example 4.2: case 6: wind alone (no temperature difference)

Here the aim might again be to achieve the same flow pattern as in Figure 4.14. This may be optimistic for some wind directions because low wind pressures on the leeward side will impede fresh air entry through openings on that side. An essential but not sufficient requirement to achieve the pattern is that the wind pressure coefficient on the upper opening must be more negative than the coefficients on the leeward side. For the present simple example, the wind direction is such that the openings are on the windward side with positive values of $C_{p\,i}$. The required flow pattern would be achieved if the internal pressure were such that the pressure difference across the upper opening is one half of the total pressure difference across the building (i.e. $\Delta p_4 = -0.5\,\rho_0\,U^2\,\Delta C_p\,/\,2$) and this condition is used here to specify Δp_0. Note that the value of Δp_4 is negative because the flow is outward.

Substituting $\Delta p_4 = -0.5\,\rho_0\,U^2\,\Delta C_p\,/\,2$ into equation 4.11 and setting $\Delta \rho_0 = 0$ (i.e. no buoyancy effect) gives Δp_0 as follows:

$$\Delta p_0 = -0.5\,\rho_0\,U^2\,[(\Delta C_p\,/\,2) + C_{p4}] \qquad (4.18)$$

Substituting for Δp_0 in equation 4.11 (again with $\Delta \rho_0 = 0$) gives the following expression for Δp_i:

$$\Delta p_i = -0.5\,\rho_0\,U^2\,[(\Delta C_p\,/\,2) + C_{p4}] + 0.5\,\rho\,U^2\,C_{p\,i}$$

$$(4.19)$$

The value of Δp_0 is first calculated. All the conditions given in Figure 4.14 apply, except that $T_I = 25$ °C. The wind pressure coefficients C_{p1} to C_{p4} are taken as 0.25, 0.25, 0.25 and -0.1 respectively. Thus ΔC_p is 0.35.

Thus the internal and external conditions are as follows:

— external temperature: $T_E = 25$ °C
— internal temperature: $T_I = 25$ °C
— temperature difference: $\Delta T_0 = 0$ K
— wind speed: $U = 3$ m·s^{-1}
— dynamic pressure: $0.5\,\rho\,U^2 = 5.4$ Pa
— reference density: $\rho_0 = 1.2$ kg·m^{-3}
— density difference: $\Delta \rho_0 = 0$ kg·m^{-3}

Equation 4.18 then gives:

$$\Delta p_0 = 1.851 \text{ Pa}$$

Equation 4.19 is then used to obtain Δp_i and equation 4.17 to obtain $C_{d\,i}\,A_i$. The results are given in Table 4.5.

The results shown in Table 4.5 may be compared with those for Example 4.1 in Table 4.2. If the two sets of weather conditions were considered to be appropriate design conditions for A_i, it would be logical to choose the areas in Table 4.2 to size the openings, because they are the larger values; i.e., in principle, the values of A_i can then be reduced by the occupants or the control system to satisfy the conditions of Example 4.2.

Example 4.3: case 6: wind and buoyancy combined

In this example the weather conditions for Examples 4.1 and 4.2 are combined. Again the same flow pattern is specified, so the value for Δp_0 is obtained by specifying that the values of Δp_i for openings 3 and 4 are opposite and equal. Thus, applying equation 4.11 gives:

$$\Delta p_0 - \Delta \rho\,g\,z_3 + 0.5\,\rho\,U^2\,C_{p3} =$$

$$- (\Delta p_0 - \Delta \rho\,g\,z_4 + 0.5\,\rho\,U^2\,C_{p4}) \qquad (4.20)$$

The internal and external conditions are as follows:

— external temperature: $T_E = 25$ °C
— internal temperature: $T_I = 28$ °C
— temperature difference: $\Delta T_0 = 3$ K
— wind speed: $U = 3$ m·s^{-1}
— dynamic pressure: $0.5\,\rho\,U^2 = 5.4$ Pa
— reference density: $\rho_0 = 1.2$ kg·m^{-3}
— density difference: $\Delta \rho_0 = 001028$ kg·m^{-3}.

Equation 4.20 then gives:

$$\Delta p_0 = 0.771 \text{ Pa}$$

Equation 4.11 is then used to obtain Δp_i and equation 4.17 to obtain $C_{d\,i}\,A_i$. The results are given in Table 4.6.

Table 4.5 Example 4.2: opening areas — wind alone

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i}\,A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	0.25	0.448	Inward	+1	0.945	0.3570	0.61	0.585
2	5.1	0.25	0.448	Inward	+1	0.945	0.3570	0.61	0.585
3	8.35	0.25	0.448	Inward	+1	0.945	0.3570	0.61	0.585
4 (outlet)	11.5	−0.1	−1.344	Outward	−1	−0.945	1.0709	0.61	1.756

Table 4.6 Example 4.3: opening areas — wind and buoyancy combined

Opening	z_i/ m	$C_{p\,i}$	q_i/ m³·s⁻¹	Flow pattern	S_i	Δp_i/ Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i/ m²
1	1.85	0.25	0.448	Inward	+1	1.9017	0.2516	0.61	0.413
2	5.1	0.25	0.448	Inward	+1	1.5165	0.2818	0.61	0.462
3	8.35	0.25	0.448	Inward	+1	1.131	0.3262	0.61	0.535
4 (outlet)	11.5	−0.1	−1.344	Outward	−1	−1.131	0.9785	0.61	1.604

4.3.3 Buoyancy alone with stratification

In large vertical structures such as atria, the assumption of uniform internal temperature may be unrealistic. Temperature stratification can be expected and it is possible to determine its effect on the opening areas. The hydrostatic equation still applies but in a modified form to take account of the variation of internal density with height. It is first necessary to specify the variation of temperature. Since the atrium is open to the internal spaces, it is assumed that there are no horizontal differences in temperature (horizontal density differences can occur with a chimney and are dealt with in section 4.3.4).

Any density variation can be chosen, but to be realistic it should be non-linear, with the greatest changes occurring at the higher levels. For the following example, the variation is specified in terms of the internal temperatures at $z = 0$ and at the neutral height, z_n, i.e. T_0 and T_n. The reason for this is that the neutral plane typically lies just above the occupied zone and is a measure of the maximum temperature in the occupied part of the building. The form of equation chosen here is as follows:

$$T + 273 = \frac{T_0 + 273}{\left[1 - \left(1 - \frac{T_0 + 273}{T_n + 273}\right)\left(\frac{z}{z_n}\right)^N\right]} \quad (4.21)$$

where T is the temperature at height z (m), T_0 is the temperature at height $z = 0$ (°C), T_n is the temperature at the neutral height z_n (°C), z is the height above ground level (m), z_n is the height of the neutral plane above ground level (m) and N is a numerical index.

The value selected for the index N is important. A value of 1 corresponds to a linear increase of temperature with height. A value of 7 is taken in the following examples. This corresponds to a more realistic case where the bulk of the temperature change occurs at the higher levels. At the initial stage of a design, choosing the values for T_n and N is best based on experience from other buildings. In the absence of such experience a range of values can be chosen, to gauge their importance. Figure 4.15 shows the effect of N on the temperature variation. (Note that the uniform temperature case is closely approximated by using a value of N that is close to, but not equal to, zero).

With the above temperature variation the equation for Δp_i with non-uniform density (equation 4.4) becomes:

$$\Delta p_i = \Delta \rho_0 \, g \, (z_n - z_i)$$
$$+ \frac{\Delta \rho_0 \, g \, z_n}{N+1} \left(\frac{\Delta T_n}{\Delta T_0} - 1\right)\left(1 - \frac{\Delta T_n}{T_n + 273}\right)\left(1 - \frac{z_i^{N+1}}{z_n^{N+1}}\right)$$
$$(4.22)$$

where ΔT_0 and ΔT_n denote the internal and external temperature differences at $z = 0$ and z_n respectively. The required areas can again be found using equation 4.17.

Example 4.4: case 6: buoyancy alone with stratification

For the following example, all of the values are the same as for Example 4.1, except that, for stratification, T_n is taken as 31 °C, i.e. $\Delta T_0 = 3$ K and $\Delta T_n = 6$ K.

The internal and external conditions are as follows:

— external temperature: $T_E = 25$ °C

— internal temperature: $T_I = 28$ °C

— internal temperature at neutral height: $T_n = 31$ °C

— temperature difference: $\Delta T_0 = 3$ K

— temperature difference: $\Delta T_n = 6$ K

— wind speed: $U = 0$ m·s⁻¹

— dynamic pressure: $0.5 \, \rho \, U^2 = 0$ Pa

— reference density: $\rho_0 = 1.2$ kg·m⁻³

— density difference: $\Delta \rho_0 = 0.01028$ kg·m⁻³

The neutral height is taken as 10 m and substituting this value into equation 4.22 enables Δp_i to be calculated. Equation 4.17 is then used to obtain $C_{d\,i} A_i$. There is no need to calculate $\Delta \rho_0$, because it is implicit in equation 4.22 (by virtue of the fact that the temperature at the neutral height is specified). However, putting $z_i = 0$ in equation 4.22 gives $\Delta \rho_0 = 1.3303$ Pa.

The corresponding temperatures at the heights of the openings are shown in Table 4.7 and in Figure 4.14.

Comparing Tables 4.7 and 4.2, it is clear that, except for the upper opening, the effect of the stratification on the
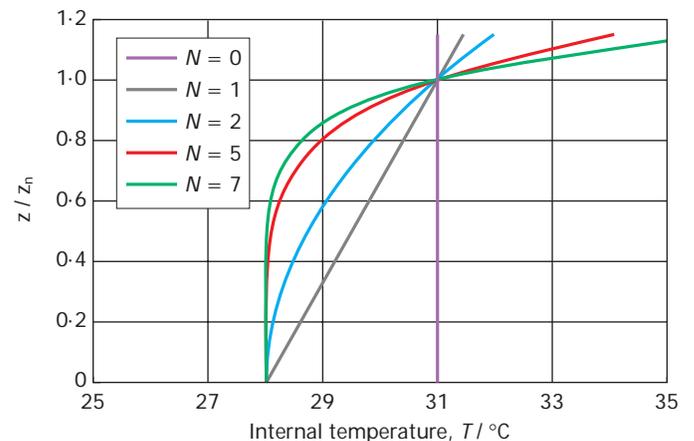
Figure 4.15 Variation of internal temperature with z/z_n for different values of N ($T_0 = 28$ °C, $T_n = 31$ °C)

Table 4.7 Example 4.4: opening areas — buoyancy only, with stratification

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	0.25	0.448	Inward	+1	1.1111	0.3292	0.61	0.540
2	5.1	0.25	0.448	Inward	+1	0.7252	0.4075	0.61	0.668
3	8.35	0.25	0.448	Inward	+1	0.3064	0.6269	0.61	1.028
4 (outlet)	11.5	−0.1	−1.344	Outward	−1	−0.4768	1.5077	0.61	2.472

Table 4.8 Example 4.4: opening areas — buoyancy only, with stratification following night cooling

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	0.25	0.448	Inward	+1	0.0169	2.6710	0.61	4.379
2	5.1	0.25	0.448	Inward	+1	0.1437	0.9154	0.61	1.501
3	8.35	0.25	0.448	Inward	+1	0.1936	0.7887	0.61	1.293
4 (outlet)	11.5	−0.1	−1.344	Outward	−1	−0.6384	1.3029	0.61	2.136

openings is small. This is expected since the temperature at the inlet heights is little different to the uniform temperature case.

Stratification allows the case where the required flow pattern is achieved, even though the internal temperatures of the occupied spaces are lower than the external temperature. This corresponds to the case, for example, where night cooling has successfully taken place. By setting $T_I = 24\ °C$ in Example 4.4 ($\Delta T_0 = -1\ K$), with all other quantities unchanged, the results shown in Table 4.8 are obtained.

4.3.4 Chimneys

Figure 4.16 shows the same space as in Figure 4.14, but ventilated by a chimney of length L. The chimney extends a distance h above the height of the occupied space, H.

Two conditions are considered, both with buoyancy alone; the first where the chimney temperature is uniform and equal to the room temperature and the second where the chimney temperature is greater than the room temperature (for simplicity, both are still assumed to be uniform).

Example 4.5: case 7: chimney temperature equal to internal temperature

For the case where $\rho_c = \rho_I$, the required area for the chimney can be obtained simply by substituting the value of $C_{d\,i}$ into the solution for case 6, Example 4.1. This is because, with no variation of density within the space, the pressure distribution is unchanged if z_n is unchanged (Note that the flow direction is upward, so $z_i = H + h$).

It should be noted that because the shape of the chimney is very different to a sharp-edged opening, its discharge coefficient can be considerably different to 0.6. If the chimney is straight with no internal obstructions and has a streamline inlet and outlet, $C_{d\,i}$ may exceed 0.6. Thus in case 6, Example 4.1, the use of a stack with $C_{d\,i} = 0.8$ instead of the sharp-edged opening would reduce the required area of the chimney to 3.02 m². However, if the stack contained several bends and a restrictive outlet with $C_{d\,i} = 0.4$, say, the area would be increased to 6.17 m². In practice it might then be preferable to retain the simpler opening and modify its shape (e.g. a bellmouth inlet) to increase $C_{d\,i}$. Another feature of chimneys is that because they tend to be long, their discharge coefficient will, in
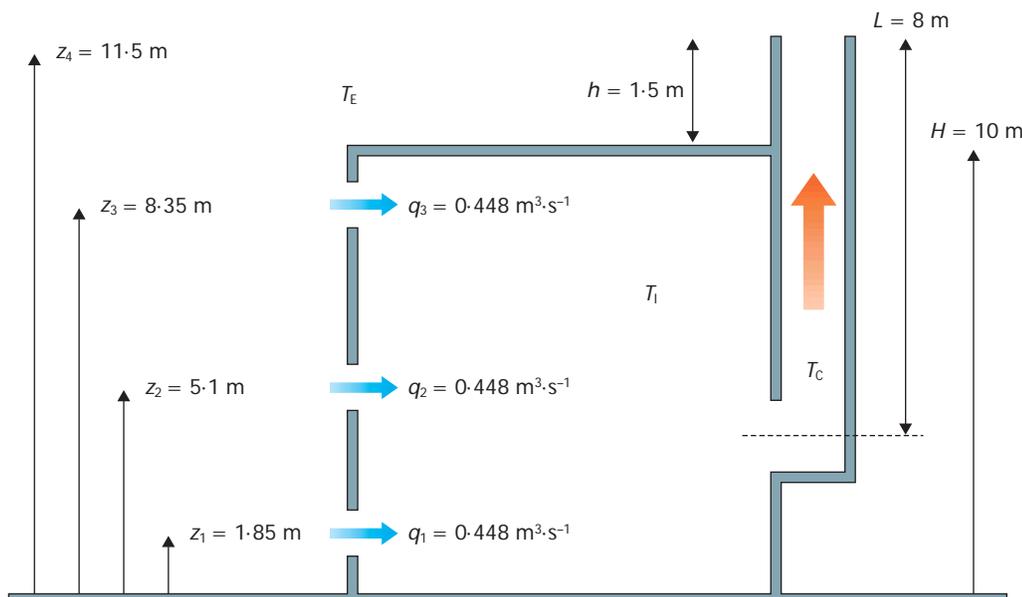
Figure 4.16 Examples 4.5 and 4.6: properties of building for case 7

principle, vary with flow rate (strictly speaking with Reynolds number), due to friction at the walls. In most cases this variation is not great and a simple iteration procedure can be used to account for it. This procedure is described in section 4.4.3. Chimneys offer a further benefit when their internal temperature is greater than T_I, as shown in Example 4.6.

Example 4.6: case 7: chimney temperature greater than internal temperature

The expression for the pressure difference for the chimney is now different to that for the other openings (which remains unchanged as equation 4.11) and is given by equation 4.4. The integral is evaluated in two stages: (*a*) up to the height of the inlet to the chimney and (*b*) over the height of the chimney. This gives:

$$\Delta p_c = \Delta p_0 - \rho_E \, g \,(H + h) + \rho_I \, g \,(H + h - L) + \rho_c \, g \, L$$

(4.23)

which can be re-arranged to give:

$$\Delta p_c = \Delta p_0 - \Delta \rho_0 \, g \,(H + h) - \Delta \rho_c \, g \, L \qquad (4.24)$$

where:

$$\Delta \rho_c = \rho_I - \rho_c \qquad (4.25)$$

In the present example the temperature in the chimney (T_c) has been set to 31 °C and the length of the chimney (L) has been taken as 8 m, but all other values are the same as Example 4.1. The flow pattern required is the same as that shown in Figure 4.14 and the value of Δp_0 is obtained by specifying that the values of Δp_i for openings 3 and 4 (the chimney) are opposite and equal, i.e:

$$\Delta p_0 - \Delta \rho_0 \, g \, z_3 = -(\Delta p_0 - \Delta \rho_0 \, g \,(H + h) - \Delta \rho_c \, g \, L)$$

(4.26)

The internal and external conditions are as follows:

— external temperature: $T_E = 25$ °C

— internal temperature: $T_I = 28$ °C

— temperature difference: $\Delta T_0 = 3$ K

— chimney temperature: $T_c = 31$ °C

— chimney temperature difference: $\Delta T_c = 3$ K

— wind speed: $U = 0$ m·s^{-1}

— dynamic pressure: $0.5 \, \rho \, U^2 = 0$ Pa

— reference density: $\rho_0 = 1.2$ kg·m^{-3}

— density difference: $\Delta \rho_0 = 0.01028$ kg·m^{-3}

— chimney density difference: $\Delta \rho_c = 0.01196$ kg·m^{-3}

— building height: $H = 10$ m

— chimney length: $L = 8$ m

— height of top of chimney above building: $h = 1.5$ m.

Equation 4.26 gives:

$$\Delta p_0 = 1.6455 \text{ Pa}$$

Equation 4.11 (with $U = 0$) is then used to obtain Δp_i and equation 4.17 to obtain $C_{d\,i} \, A_i$. The results are given in Table 4.9.

With $C_{d\,i} = 0.8$ the required chimney area is 1.607 m^2. (With $C_{d\,i} = 0.4$, the required chimney area is 3.213 m^2.)

Evaluating the neutral height for the occupied space reveals that it is greater than the height of the building, i.e. $z_n = 13.88$ m. The areas required for the inlet openings are correspondingly reduced compared to Example 4.1. This is now possible because setting the value of Δp_0 and the neutral height does not have the same physical interpretation that it had in the examples for case 6 (Examples 4.1 to 4.4).

As with case 6, it is also possible to treat the case of a space with T_I less than T_E while retaining the same flow pattern. By setting $T_I = 24$ °C ($\Delta T_0 = -1$), with all other quantities unchanged, the results shown in Table 4.10 are obtained. This means that Δp_i increases with height from its value of Δp_0 at ground level. The areas can be compared with those in Example 4.1 (Table 4.4).

Table 4.9 Example 4.6: opening areas — chimney; chimney temperature greater than internal temperature

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	0.25	0.448	Inward	+1	1.4263	0.2906	0.61	0.476
2	5.1	0.25	0.448	Inward	+1	1.0411	0.3401	0.61	0.558
3	8.35	0.25	0.448	Inward	+1	0.6560	0.4285	0.61	0.702
4 (outlet)	11.5	–0.1	–1.344	Outward	–1	–0.6560	1.2854	0.8	1.607

Table 4.10 Example 4.6: opening areas — chimney; internal temperature less than external temperature

Opening	z_i / m	$C_{p\,i}$	q_i / m³·s⁻¹	Flow pattern	S_i	Δp_i / Pa	$C_{d\,i} A_i$ / m²	$C_{d\,i}$	A_i / m²
1	1.85	0.25	0.448	Inward	+1	0.7908	0.3902	0.61	0.640
2	5.1	0.25	0.448	Inward	+1	0.9192	0.3619	0.61	0.593
3	8.35	0.25	0.448	Inward	+1	0.3390	0.3390	0.61	0.556
4 (outlet)	11.5	–0.1	–1.344	Outward	–1	–1.0476	1.0171	0.8	1.271
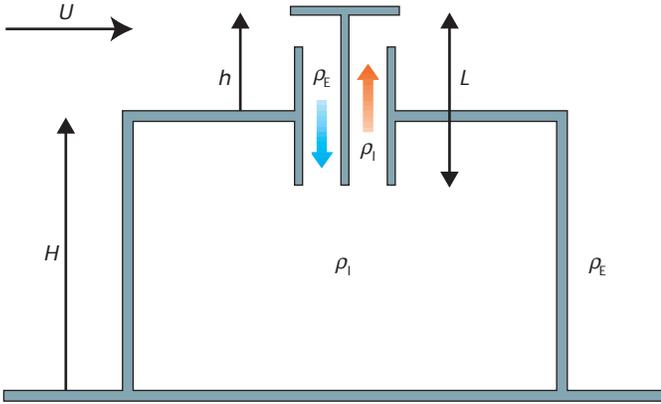
Figure 4.17 Examples 4.7 and 4.8: properties of building for case 8, space ventilated by two chimneys

Figure 4.18 Non-dimensional results of explicit model showing effect of stratification

Example 4.7: case 8: combined chimneys for inlet and outlet (buoyancy alone)

Figure 4.17 illustrates a system whereby a space is ventilated by a roof mounted pair of identical chimneys, with one acting as the inlet and the other as the outlet. There are no other openings. Note that the results apply equally to the case where the chimneys are separate.

When there is no wind, the values of Δp_i for the inlet and outlet chimneys are given respectively by equation 4.2 as:

$$\Delta p_1 = \Delta p_0 - \Delta \rho_0 \, g \, (H + h - L) \qquad (4.27)$$

$$\Delta p_2 = \Delta p_0 - \Delta \rho_0 \, g \, (H + h) \qquad (4.28)$$

Since there are no other openings, $q_1 = -q_2$ and, when the chimneys are identical, $\Delta p_1 = -\Delta p_2$. It then follows that Δp_0 is fixed and given by:

$$\Delta p_0 = \Delta \rho_0 \, g \, (H + h - L/2) \qquad (4.29)$$

This leads to the same result as for case 1, i.e:

$$C_{di} \, A_i = q_i \sqrt{\frac{\rho_0}{\Delta \rho_0 \, g \, L}} = q_i \sqrt{\frac{T_E + 273}{\Delta T_0 \, g \, L}} \qquad (4.30)$$

With $T_E = 25$ °C, $\Delta T_0 = 3$ K, $q_i = 0.448$ m³·s⁻¹ and $L = 3$ m:

$$C_{di} \, A_i = 0.823 \text{ m}^2$$

Example 4.8: case 8: combined chimneys for inlet and outlet, wind alone

For this example, the building is the same as that used for Example 4.7 (Figure 4.17).

The result for the 'wind alone' case is the same as that for case 4, i.e:

$$C_{di} \, A_i = \frac{q_i}{U} \sqrt{\frac{2}{\Delta C_p}} \qquad (4.31)$$

where $\Delta C_p = C_{p1} - C_{p2}$.

With $C_{p1} = 0.25$, $C_{p2} = -0.1$, $q_i = 0.448$ m³·s⁻¹ and $U = 3$ m·s⁻¹:

$$C_{di} \, A_i = 0.357 \text{ m}^2.$$

Table 4.11 Example 4.1: determination of inlet area for three cases of stratification

z_i / z_n	$\Delta T_n / \Delta T_0$	$\Delta p_i / \Delta \rho_0 \, g \, z_n$	Δp_i / Pa	$C_{di} A_i$ / m²	C_{di}	A_i /m²
0.51	1 (uniform)	0.49	0.58	0.46	0.61	0.75
0.51	2	0.61	0.72	0.41	0.61	0.67
0.51	3	0.75	0.89	0.37	0.61	0.60

4.3.5 Non-dimensional graphs

Figure 4.18 shows the non-dimensional pressure difference, $\Delta p_i / \Delta \rho_0 \, g \, z_n$, as a function of non-dimensional height, z_i / z_n for three different cases of stratification, i.e. $\Delta T_n / \Delta T_0 = 1$, 2 and 3. The first case is the uniform density case and equation 4.16 appears as a straight line.

It is a simple matter to calculate the open area required for an opening. Taking the opening at height 5.1 m in case 6 with the neutral height at 10 m, the value of z_i / z_n is 0.51. The corresponding value of $\Delta p_i / \Delta \rho_0 \, g \, z_n$ is read from Figure 4.18 for uniform temperature as 0.49. Since $\Delta \rho_0 \, g \, z_n = 1.185$ Pa, $\Delta p_i = 0.58$ Pa. Substituting into equation 4.17 gives $C_{di} A_i = 0.46$. The same procedure can be used for the cases with stratification to give the areas shown in Table 4.11.

The results for $\Delta T_n / \Delta T_0$ equal to 1 and 2 can be compared with the corresponding values in Tables 4.2 and 4.7 respectively. Although less precise, the agreement is adequate.

As noted in section 4.3.2, the effect of stratification with $\Delta T_n / \Delta T_0 = 2$ is small, with a reduction in area of about 10%. With $\Delta T_n / \Delta T_0 = 3$, the reduction increases to 20%. For the upper opening, $z_i / z_n = 1.15$, the reductions are more substantial.

4.4 Input data requirements and selection

Before any of the design methods described in section 4.3 can be used, appropriate input data must be identified. In this section, the data items are reviewed and guidance provided on sources of useful information.

4.4.1 External wind pressures

Wind pressures are usually expressed in the form of a pressure coefficient, $C_{p\,i}$, defined by equation 4.6. The reason for this is that, unlike $p_{w\,i}$, $C_{p\,i}$ does not vary greatly with wind speed. This is primarily due to the fact that sharp edges on the building fix the positions of flow separation. Thus for a given building shape and surrounding environment (which determines the characteristics of the approaching wind) the $C_{p\,i}$ distribution depends only on wind direction and the position of the point where wind speed (U) is measured. Surface pressure coefficients for different generic building forms are available[63,64]. Pressure coefficients for specific buildings can be estimated from these generalised data sets or they can be generated from wind tunnel studies (see section 4.2.7) or, possibly, by CFD (see section 4.2.5).

In general terms, the pressure coefficient of an unobstructed building surface is positive on facades facing the wind and negative on other surfaces. The negative pressures are often associated with flow separation. This means that roofs with slopes less than 30° are usually in a low pressure region, irrespective of wind direction. Positive pressures may be experienced on roofs of greater pitch, or on deep flat roofed buildings where flow re-attachment may occur.

The data on wind pressure coefficients are extensive and reference must be made elsewhere for further information[63,64]. Figure 4.19[63] shows the sort of information that is available.

Stacks and chimneys usually extend above roof level. It is important to ensure that they are in a low pressure area to eliminate the possibility of reverse flow in strong winds. Guidance for this is available elsewhere[64]. The recommendations for siting flue terminals for gas appliances[65] may also be of some help, although it must be remembered that temperatures are much higher than those encountered with natural ventilation.

It is important that the correct value of wind speed (U) is used when evaluating $p_{w\,i}$, because it is proportional to U^2, and, in the absence of buoyancy, flow rates are proportional to U. The $C_{p\,i}$ data set should specify the height at which the reference wind speed was measured and the nature of the terrain surrounding the building. The designer will probably not have wind speed records for the
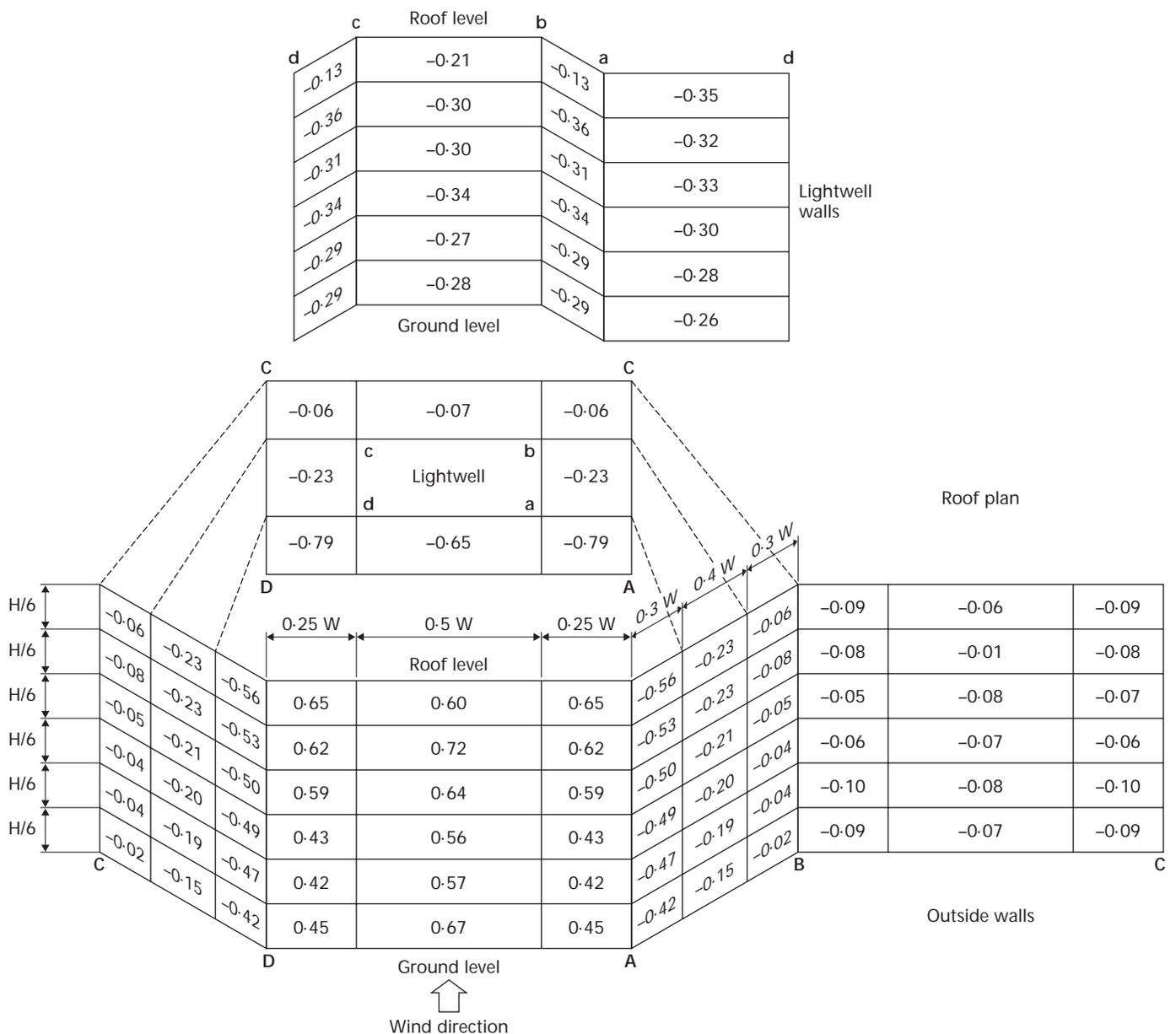
Figure 4.19 Examples of wind pressure coefficient data[62]

reference position and it is then necessary to estimate the values of U from the data available, e.g. from Met Office records for a site that could be many kilometres from the building. The procedure[62] described below may be used, although it is subject to uncertainty associated with changes of terrain between the building and the Met Office site.

A more recent procedure is that used for evaluating structural loads on buildings[34]. This would need to be adapted for ventilation calculations, because the aim is to determine the magnitude of a 3-second gust, which is not relevant to ventilation. However if the procedure were applied to the building as part of the structural design, the effort involved in applying it to ventilation design may be justifiable.

The uncertainty associated with determining wind pressures is another reason why the treatment of ventilation due to wind is less precise than for buoyancy alone. It may be worthwhile to assess how important the effects of wind are to the design compared to buoyancy. In this connection it can be noted that, for a summer design condition, the wind is likely to be less important than buoyancy because the main problem is to achieve adequate ventilation under no-wind conditions. For a winter design condition, when the temperature difference is large, buoyancy can be the dominant driving force at relatively high wind speeds.

4.4.1.1 Determination of wind speed for evaluating wind pressure coefficient[62]

The wind speed (measured at a height of 10 m in open country) at the Met Office site is denoted by U_{met}. The $C_{p\,i}$ values use wind speed measured at height z. For a given value of U_{met}, the wind speed at height z is given by:

$$U = U_{met}\,k\,z^a \tag{4.32}$$

where U is the wind speed at height z (m·s⁻¹), z is height above ground (m), k and a are coefficients determined by the terrain in which the building lies.

Values for the terrain coefficients are given in Table 4.12. For example, if the building is situated in urban terrain and the wind speed at height $z = 20$ m is required, then:

$$U = U_{met}\,0.35\,z^{0.25}$$

Thus, for $U_{met} = 4$ m·s⁻¹, say, the wind speed to be used for calculating pressures is $U = 2.9$ m·s⁻¹.

The designer will need to choose a value for U_{met} corresponding to a probability that it will not be exceeded; this can be done using tabulated data derived from meteorological records[62].

4.4.2 Specification of densities

Buoyancy is much easier to treat than wind because temperatures are subject to much less uncertainty. Accurate records of external temperature are widely available and the appropriate values will have been defined by the weather data used for the design. The internal temperatures can be taken as the design temperature specified for each of the internal spaces.

Table 4.12 Terrain coefficients[18]

Terrain	k	a
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.2
Urban	0.35	0.25
City	0.21	0.33

It is important to remember that all calculations of density should be based on air temperature rather than, say, dry resultant temperature. When carrying out sizing calculations such as those in section 4.3 it is important to use a relatively accurate value for $\Delta\rho$, but the value used for ρ is less important. This is consistent with the neglect of ρ in equation 4.9 for the explicit method. Consequential errors in A_i should usually be less than 10 %.

For the worked examples given in sections 4.3 and 4.4, the following approximations have been used:

$$\frac{\Delta\rho_0}{\rho_0} = \frac{T_I - T_E}{T_E + 273} \tag{4.33}$$

$$\frac{\Delta\rho_c}{\rho_0} = \frac{T_c - T_I}{T_I + 273} \tag{4.34}$$

The reference density ρ_0 has been taken as 1.20 kg·m⁻³. The reference density could equally well have been taken as the average of the internal and external values, in which case the calculated values of A_i would have differed by a few percent.

These approximations are usually adequate. If the absolute pressure and relative humidity are specified as well as the air temperature, a precise value of $\Delta\rho$ can be obtained by subtracting the densities evaluated in the manner described in CIBSE Guide C[66]. In general, the sizing of openings does not warrant such precision, partly because the sizes of commercially available air vents etc. are unlikely to match precisely the calculated values. Moreover, the uncertainties associated with the calculation procedure, particularly when wind is present, will generally exceed those in the evaluation of $\Delta\rho$.

4.4.3 Discharge coefficients and areas of openings

Explicit methods give the required value of $C_{d\,i}\,A_i$ for each purpose-provided opening. It is then necessary to select an opening that has this value, either from manufacturers' data or by specifying the dimensions of a bespoke opening. It is the product $C_{d\,i}\,A_i$ that matters, but it is necessary that the values of $C_{d\,i}$ and A_i are consistent with one another. Procedures for determining these values for purpose-provided openings are described below. These procedures can also be used for implicit methods, which require the specification of $C_{d\,i}\,A_i$. Implicit methods can also account for adventitious openings and these are dealt with separately.

4.4.3.1 Purpose-provided openings

Ideally manufacturers' data for an opening will provide the value of C_d and the value of A_i on which $C_{d\,i}$ is based. It is then simply a matter of multiplying these two values and selecting the opening which gives the closest value to

the required value of $C_{d\,i}\,A_i$. With small openings such as air vents it is not uncommon for the 'effective area' (A_{eff}) of the vent to be quoted. The effective area is usually defined as the area of a sharp-edged circular orifice that gives the same flow rate as the opening at a given pressure difference. Since the discharge coefficient of a circular orifice is taken as 0.61, the product 0.61 A_{eff} is used to select the opening. Sometimes a geometric area, A_g, is quoted with a discharge coefficient C_{dg}. In this case the product $A_g\,C_{dg}$ should be used. The geometric area is often called the 'free area' or the 'open area'.

Manufacturers' data will almost certainly have been obtained from still-air tests. This corresponds to the buoyancy-alone condition and the data can be applied with confidence to this case. The discharge coefficient $C_{d\,i}$ can be expected to change in the presence of wind but there are few data available so the still-air value will usually have to be used as a default. For openings that lie flush with the envelope, the effect of wind is likely to be a relatively small reduction in $C_{d\,i}$. For openings that protrude into the flow, the effects of wind may be large and can reduce or increase $C_{d\,i}$ depending on the local flow direction relative to the opening. Basically, the protrusion can deflect flow into or out of the opening and the concept of the discharge coefficient becomes less tenable. This is particularly the case for windows with openable vanes.

Data provided by the manufacturer should always be used where possible. If such data are not available, the following procedures may be used.

(a)   Simple estimation

The shape of open windows is usually such that $C_{d\,i}$ can be taken as 0.6 with A_i taken as the minimum geometric open area of the device, measured in a plane normal to the flow path through the opening. This is illustrated in Figure 4.20 and the dimension d should be used to evaluate the area. The same applies to a single grille. Where two grilles are used in series, as shown in Figure 4.20(b), the value of $C_{d\,i}$ for the combination should be reduced to 0.4, with A_i being taken as the area of the single grille.

(b)   Use of tabulated loss coefficients

For long openings, such as chimneys and ducts, $C_{d\,i}$ can be evaluated from tabulated loss coefficients (C_L) of the components. The procedure is essentially the same as that used for pressure losses in mechanical ventilation ducts. The results are likely to be less accurate, however, partly because natural ventilation ducts tend to be short, so the requirement for fully developed flow may not be satisfied. Also, flow rates, and hence Reynolds numbers, tend to be low and may lie outside the range of tabulated data. Figure 4.21 shows a simple circular chimney with diameter d and total length L from inlet to outlet. The inlet and outlet are plain and there is one bend.

The discharge coefficient can be obtained from the loss coefficients for the inlet, the bend and the outlet and the frictional loss coefficient for the length L[51], i.e:

$$C_{d\,i} = \sqrt{\dfrac{1}{C_{L(in)} + C_{L(bend)} + C_{L(out)} + (4\,L\,c_f\,/\,d)}}$$

(4.35)

where $C_{L(in)}$ is the loss coefficient for the inlet, $C_{L(bend)}$ is the loss coefficient for the bend, $C_{L(out)}$ is the loss coefficient for the outlet, L is the total length of the chimney (m), d is the diameter of the chimney (m) and c_f is the friction coefficient.

The fourth term on the right-hand side is the skin friction term and this will lead to a dependence of discharge coefficient on Reynolds number. The Reynolds number (Re) is defined by:

$$Re = \dfrac{\rho\,q\,d}{A\,\mu} = \dfrac{4\,\rho\,q}{\pi\,d\,\mu}$$

(4.36)

Figure 4.20 Estimation of $C_{d\,i}$ and A_i for windows and air vents; (a) top hung window, (b) two grilles in series
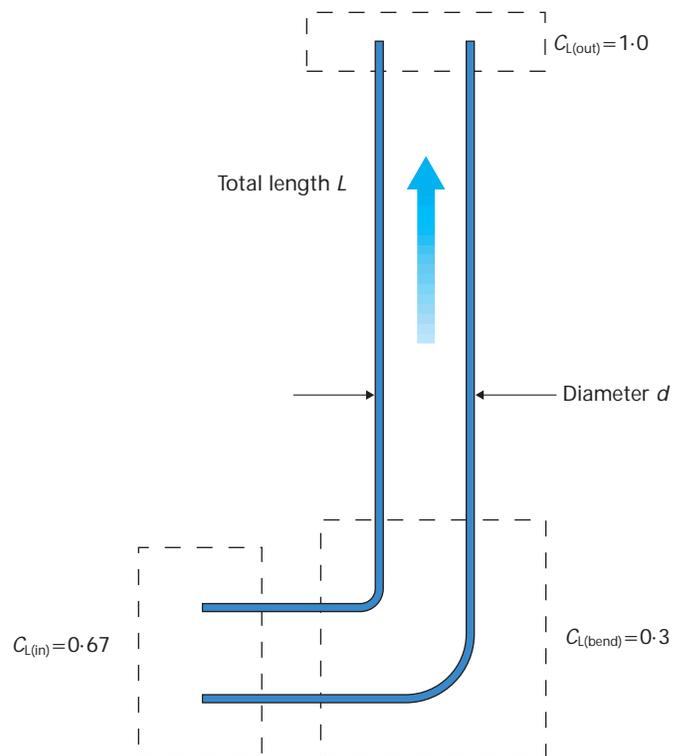
Figure 4.21 Estimation of $C_{d\,i}$ for a simple chimney

where Re is the Reynolds number, ρ is the air density (kg·m^{-3}), q is the flow rate (m^3·s^{-1}), d is the diameter (m), A is the area (m^2) and μ is the viscosity of air (kg·m^{-1}·s) and can be taken as 1.8×10^{-5}.

For turbulent flow in the chimney, the skin friction term in equation 4.35 can be taken as $(0.316\, L\, /\, Re^{0.25}\, d)$. Since the purpose of the explicit calculation is to determine d, it is necessary to make an initial guess of its value to evaluate this term.

For example, in Example 4.6 above the flow in the chimney is 1.344 m^3·s^{-1}. Taking $d = 1.0$ m as the initial guess gives $Re = 1.14 \times 10^5$ and the friction term as 0.137. Using the loss coefficients given in Figure 4.21, equation 4.35 gives $C_{d\,i} = 0.673$. From the results for Example 4.6, $C_{d\,i} A_i = 1.2854$, so the value of $C_{d\,i} = 0.673$ corresponds to an area of 1.91 m^2, i.e. $d = 1.56$ m. This is considerably larger than the initial guess. Recalculating using this new value for d gives $C_{d\,i} = 0.679$. This is only slightly different to the original value of 0.673, so we can take this value as being of sufficient accuracy. Using this value gives the area as 1.89 m^2. Basically the results are not very sensitive to Reynolds number because the chimney is not very long and friction is not a major loss. In comparison, if the plain inlet were replaced by a bellmouth inlet (for which $C_{L(in)} = 0$), $C_{d\,i}$ increases to 0.84 and A_i reduces to 1.54 m^2.

(c) Use of computational fluid dynamics (CFD)

A potentially accurate procedure is to determine $C_{d\,i}$ using CFD. This procedure may be justifiable for large components such as chimneys or complicated outlets, .

(d) Direct use of tabulated data

Data compilations of discharge coefficients are sometimes included with loss coefficients[67] for certain generic shapes of opening.

(e) Use of scale models

For large sharp-edged openings such as windows, $C_{d\,i}$ can be obtained by measurements on scale models. This technique can reveal the effects of wind.

It is important to note that in certain situations the simple discharge coefficient cannot accurately describe the flow. As mentioned in (a) above, this can occur due to the presence of wind. It can also occur when buoyancy predominates if the vertical dimension of the opening is large in relation to the height of the ventilated space. In such cases there may be inflow at the bottom and outflow at the top of the opening due to the variation in pressure gradient either side of the opening. For an isolated room, bi-directional flow through an opening may form part of the design, see case 2 in section 4.3.1. In such cases the discharge coefficient is not appropriate and is replaced by a coefficient C defined in terms of $\Delta\rho$. Empirical data are available for such cases, including those where buoyancy and wind are combined. In this way they can be included in envelope flow models[51].

4.4.3.2 Adventitious openings

Adventitious openings are those openings that are not purpose-provided such as cracks in window frames, pen-etration of walls by services, junctions between envelope components and porosity of walls. Their magnitude is usually expressed as a leakage flow rate rather than as an opening area. The leakage of an envelope is the flow rate that occurs when the envelope is subjected to a specified pressure difference (often 50 Pa). The desirability of reducing leakage through adventitious openings has long been recognised and it is now incorporated in Part L2 of the Building Regulations[5].

In many cases, adventitious openings cannot be identified and they are then referred to as 'background openings'. Openings in doors and windows can be identified (in terms of their position) and are known as 'component openings'. Component openings can be treated in an implicit envelope model in the same way as purpose-provided openings, provided their size can be estimated. CIBSE Guide C[66] gives advice on this; BS 6375[68] gives information on air leakage classification of openable windows and doors. Information on the measured performance of real components is available in the ventilation literature.

For background openings it is best to deal in terms of their leakage characteristics. At the early stage of a design it may be justifiable to treat component openings in the same way and to consider the total adventitious leakage of the envelope.

Adventitious leakage is of more concern for the winter condition, when the areas of purpose-provided openings are at a minimum to conserve heating energy. In the summer, assuming windows are open, the adventitious leakage can be neglected. With a leaky envelope, the flow through adventitious openings ('infiltration') may exceed the flow through the air vents. This is clearly undesirable and the designer may wish to check the effect of adventitious leakage. Envelope flow models are the only feasible way of calculating the effect of adventitious leakage, for which it is necessary to specify the leakage characteristic of the envelope.

4.4.4 Calculating effect of adventitious leakage

The leakage characteristic of an envelope is the relationship between the flow rate (Q_L) and the uniform pressure difference (Δp_L) across the envelope generated by a fan pressurisation test. The relationship is usually taken to be of a power law or quadratic form, i.e:

$$Q_L = \alpha\,(\Delta p_L)^{\beta} \tag{4.37}$$

or

$$\Delta p_L = a\,Q_L^2 + b\,Q_L \tag{4.38}$$

where α, β, a and b are leakage coefficients.

The best way of specifying the adventitious leakage of a building is by measurement for which there are recognised pressurisation techniques, see CIBSE TM23[24]. At the design stage measurement may be impossible, in which case the leakage can be estimated using tabulated values for different types of components and construction, as mentioned above. Such estimates are subject to considerable uncertainty. The designer may therefore wish

to carry out calculations for a range of adventitious leakage rates to ascertain its potential importance. Such calculations can be carried out using an envelope flow model. A quicker procedure is to make use of calculation results that have been plotted in non-dimensional form.

Figure 4.22[54] is a plot of the non-dimensional infiltration rate (i.e. ventilation due solely to adventitious leakage) against the non-dimensional leakage parameter. The non-dimensional infiltration rate and the non-dimensional leakage parameter are defined thus:

$$\text{Non–dim. infiltration rate} = \frac{Q_{inf}}{\sqrt{\Delta \rho \, g \, z_n / 2 \, a}} \qquad (4.39)$$

$$\text{Non–dim leakage parameter} = \frac{1}{\sqrt{\Delta \rho \, g \, z_n \, a / b^2}}$$

$$(4.40)$$

Figure 4.22 is for the case of buoyancy alone with the neutral height chosen such that the flow pattern is the same as in Example 4.1, i.e. all outward flow occurs through adventitious openings above the occupied spaces. By calculating the infiltration rate and comparing it with the design ventilation rate provided by the purpose-provided openings alone, the designer can assess the importance of the adventitious openings. If the infiltration rate exceeds the design rate, it may be advisable to consider remedial work on reducing the adventitious leakage.

To calculate Q_{inf} it is first necessary to determine a and b from the leakage characteristic. If the characteristic has been measured it is simply a matter of fitting equation 4.38 to the measured points.

It is likely that only a value for the leakage at a pressurisation of 50 Pa will be known (Q_{50}). In this case, the value for a / b^2 can be taken as 0.1 (this corresponds to a power law index $\beta = 0.67$). The value of a is then given by:

$$a = 32.1 / Q_{50}^2 \qquad (4.41)$$

where Q_{50} is the leakage rate at a pressurisation of 50 Pa ($m^3 \cdot s^{-1}$).
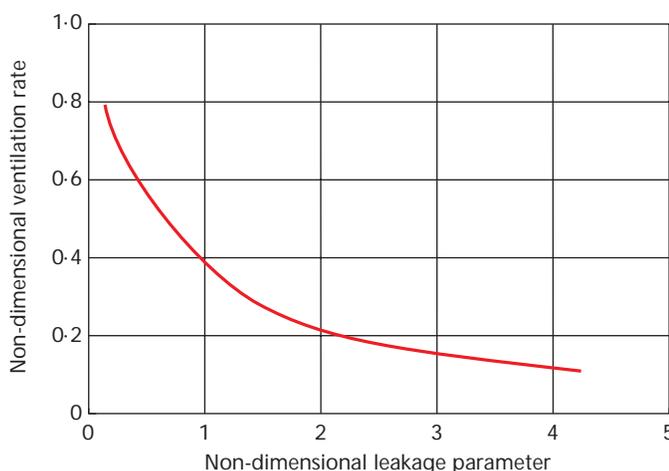
Figure 4.22 Graph for calculating infiltration rate, buoyancy alone

Using the same information as for Example 4.1:

$$\Delta \rho_0 \, g \, z_n = 1.185 \text{ Pa}$$

Suppose that the value of Q_{50} is 2.0 $m^3 \cdot s^{-1}$. Then, from equation 4.41, $a = 8.025$. Thus, from equation 4.40, the non-dimensional leakage parameter is 2.05. Therefore from Figure 4.22, the non-dimensional infiltration rate is 0.21. Hence from equation 4.39, $Q_{inf} = 0.057$ $m^3 \cdot s^{-1}$. This is the total infiltration rate and can be compared with the design rate of $3 \times 0.448 = 1.344$ $m^3 \cdot s^{-1}$. Not surprisingly, the infiltration rate is negligible. However, for the winter design condition, the design ventilation rate will be much lower and $\Delta \rho_0 \, g \, z_n$ will be higher. For example with $\Delta \rho_0 \, g \, z_n = 8$ Pa, $Q_{inf} = 0.32$ $m^3 \cdot s^{-1}$, which may exceed the design ventilation rate.

4.5　　Reservoir effect

It is quite common to specify the design flow rate of air as that required to limit the concentration of a pollutant to a fixed value. For example, the aim is often to limit the concentration of CO_2 in a space to 1000 ppmv (volumetric parts per million). When the source of pollution is the occupants alone, this requirement is deemed to maintain body odours at an acceptable level. It takes time for the concentration to increase from its initial value (the reservoir effect) and if the occupancy period is known, allowance for this can be made in specifying the design air flow rate.

For a well-mixed space, the change in CO_2 concentration with time is given by:

$$C(t) = C_{ext} + \frac{q_{CO2} \times 10^6}{Q}$$
$$- \left(C_{ext} - C(0) + \frac{q_{CO2} \times 10^6}{Q} \right) \exp \left(-\frac{Q \, t}{V} \right)$$

$$(4.42)$$

where $C(t)$ is the concentration at time t (ppmv), t is time (s), C_{ext} is the concentration in the external air entering the space (ppmv), q_{CO2} is the volumetric emission rate of CO_2 ($m^3 \cdot s^{-1}$), Q is the volume flow rate of air entering the space ($m^3 \cdot s^{-1}$), $C(0)$ is the concentration at time 0 (ppmv) and V is the volume of the space (m^3).

Equation 4.42 follows from the mass balance for CO_2. It assumes that the amount of CO_2 present in a given volume is always very much less than the amount of air, so Q can be taken as the volume flow rate of the mixture.

In the following, the assumption is made that $C(0) = C_{ext}$. The steady state concentration, C_{ss}, is obtained by making t tend to infinity and is given by:

$$C_{ss} = C_{ext} + \frac{q_{CO2} \, 10^6}{Q} \qquad (4.43)$$

where C_{ss} is the steady state concentration (ppmv).

The flow rate of air required to ensure that C_{ss} does not exceed a certain value is thus given by:

$$Q_{ss} = \frac{q_{CO2}\,10^6}{C_{ss} - C_{ext}} \qquad (4.44)$$

where Q_{ss} is the steady state flow rate ($m^3 \cdot s^{-1}$).

It is this value that is commonly used for the design flow rate.

Although C_{ss} can in principle only be reached after an infinite time, the concentration will reach 95% of C_{ss} after a finite time, t_{95}. If the occupancy period is known to be less than t_{95}, the air flow rate can be reduced by specifying that C_{ss} be reached at the end of the occupancy period.

Equations 4.42 and 4.44 can be combined to give:

$$\frac{Q_{oc}}{Q_{ss}} = 1 - \exp\left(-\frac{Q_{oc}\,t_{oc}}{V}\right) \qquad (4.45)$$

where Q_{oc} is the flow rate required to give C_{ss} at the end of the occupancy period ($m^3 \cdot s^{-1}$) and t_{oc} is the occupancy period (s).

Example 4.9: Determination of flow rate to limit CO_2 concentration

A lecture theatre with a volume of 3000 m^3 is occupied by 100 people. The emission rate of CO_2 per person is 5.56×10^{-6} $m^3 \cdot s^{-1}$ (20 litres per hour). The design concentration is 1000 ppmv and the external and initial concentrations are both equal to 350 ppmv. Equation 4.44 gives the steady state flow rate as $Q_{ss} = 0.854$ $m^3 \cdot s^{-1}$ (3075 $m^3 \cdot h^{-1}$). The corresponding form of equation 4.45 is shown in Figure 4.23. It can be seen that if the occupancy period does not exceed 1.5 hours, the air flow rate can be reduced to about $0.6 \times Q_{ss}$, i.e. 0.512 $m^3 \cdot s^{-1}$ (1845 $m^3 \cdot h^{-1}$).

Figure 4.23 also implies that with an occupancy period less than about 1 hour, no ventilation is required. This is due to the fact that even with no ventilation it takes nearly 1 hour for the concentration to reach 1000 ppmv. This can be seen by making Q tend to zero in equation 4.42 and expanding the exponential term to give:

$$C(t) = C(0) + \frac{q_{CO2}\,10^6}{V}\,t \qquad (4.46)$$

Using the values in Example 4.9, equation 4.46 gives the time to reach 1000 ppmv as 3508 s.
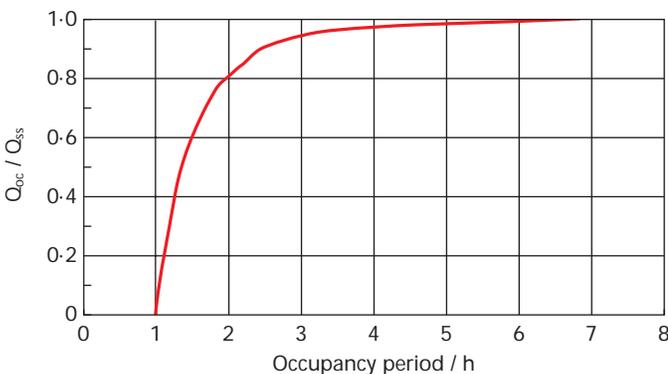
Figure 4.23 Example 4.9: effect of occupancy period on ventilation rate required to achieve 1000 ppmv CO_2
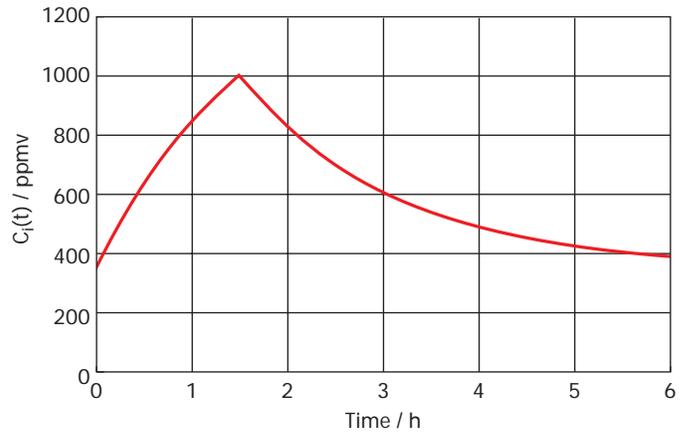
Figure 4.24 Example of concentration decay following a period of occupancy

The reservoir effect offers significant reductions in ventilation rates, but it must be remembered that after the occupancy period there needs to be a period to allow the concentration to decrease prior to the next occupied period. Low ventilation rates could also of course lead to other problems, e.g. overheating of occupants.

Equation 4.42 can be used to calculate the time required for the concentration to drop to an acceptable level (by restarting the calculation with $t = 0$, $C(0) = 1000$ and $q_{CO2} = 0$. This is illustrated in Figure 4.24 for the lecture room where the ventilation rate has been taken as 0.512 $m^3 \cdot s^{-1}$ and the occupancy period as 5400 s (1.5 h). It can be seen that with this ventilation rate, several hours are required for the concentration to fall to the external level.

Note: the above equations assume that the pollutant is well mixed. This is likely to be a reasonable assumption when the ventilation rate is high, but less so with a low ventilation rate and/or a high ceiling, where stratification may be significant. Stratification will however tend to act in a beneficial way, by leading to higher concentrations above the occupied zone.

Equation 4.42 differs from the equation given in BS 5925[62] in two respects. First, it includes the initial concentration. Secondly, the treatment of the mass flow associated with the pollutant is different and is more appropriate for carbon dioxide, which is formed from the air within the space and does not correspond to an extra mass flow into the space, unlike some other pollutants or a tracer gas. This only leads to differences when Q is very small, i.e. of similar magnitude to q_{CO2}. *Note*: equation 4.42 is included in the spreadsheet* that may be obtained from the CIBSE website.

4.6 Complementary design techniques

As has been stressed throughout this publication, the design of the natural ventilation system has to be carefully integrated with the other elements of the design. A building will not be regarded as acceptable if the lighting or acoustic environments are poor, even if the ventilation strategy is working perfectly. Guidance on design methods is available in other CIBSE publications.

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* The spreadsheet may be downloaded from the CIBSE website (www.cibse.org/venttool)

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Foreword

The need for the Institution to provide professional guidance on the design and application of natural ventilation in buildings was first identified when I was CIBSE President in 1992. The resulting Applications Manual was first published in 1997 with the aim of 'providing more guidance on energy related topics in order to realise quickly the improvements in energy efficiency which should arise from the application of the guidance presented'.

Much has happened since 1997 in relation to energy use in buildings. The Energy Efficiency Best Practice Programme which sponsored the first edition has been replaced by the Carbon Trust, which has become very widely recognised for its high profile campaigns raising awareness of business use, and waste, of energy. Part L of the Building Regulations, *Conservation of Fuel and Power*, has been transformed and will shortly be revised once more as Part L (2005). The Energy Performance in Buildings Directive has been adopted by the EU, and will be implemented in the UK from the start of 2006. And, late in 2004, the Sustainable and Secure Buildings Act reached the statute book, to enable Building Regulations to address these two, sometimes conflicting, themes.

In the light of all these changes, as well as the growing practical experience of advanced naturally ventilated buildings, it is timely to issue a revised edition of this guidance. The principles remain largely unchanged — as do the laws of physics on which they depend. However, experience in their application has advanced, and new examples have appeared. As a result, the material has been re-ordered, and the examples, instead of standing alone at the end, are now incorporated within the guidance at appropriate places. This edition also draws extensively on work funded by the Partners in Innovation scheme of the DTI on automatic ventilation devices. The guidance contained within this edition will enable practitioners to apply the principles of natural ventilation based on a sound understanding of their underlying basis. In so doing further improvements in energy efficiency will be achieved.

The revision has been undertaken by one of the original authors, Steve Irving, aided by David Etheridge and Brian Ford of Nottingham University. The revision has again been steered by a small group of leading practitioners from a range of professional backgrounds, with the aim of producing guidance that is as far as possible accessible to architects and engineers alike, and will assist them in adopting an integrated approach to building design. The Institution would like to thank the Steering Group, listed below, for their contribution to the project, and also to acknowledge the support of the Carbon Trust for the work.

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AM10 Steering Group

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INDEX

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Index Terms	Links			
CIBSE AM11: *Building energy and environmental modelling*	37			
CIBSE AM13: *Mixed mode ventilation*	8			
CIBSE Guide A: *Environmental design*	1			
climate change data	5			
comfort	38			
heat island effect	5			
small power load gains	6			
thermal capacity	7			
ventilation rate calculations	37	46		
whole–building ventilation	3			
wind speeds	14			
CIBSE Guide B2: *Ventilation and air conditioning*	1	2		
CIBSE Guide C: *Reference data*	55	57		
CIBSE Guide J: *Weather, solar and illuminance data*	14	38		
CIBSE TM23: *Testing buildings for air leakage*	57			
CIBSE TM31: *Building log books*	35			
CIBSE TM37: *Design for improved solar control*	4	5		
Circulation areas	10			
Cleanliness	10	27	36	
Climate change	1–2	4–5	38	
see also Weather data				
Closed loop control	34			
CO_2 levels	3	36	58–59	
Coatings	4	6		
Code for lighting	5			
Combined models	2	41	43	
Combined occupant and automatic control	3–5	23		
Combined openings	23	26–27		
Combined wind and stack ventilation	14–15	18	49–50	55
	57			
Combined window types	23	26		
Comfort	6–7			
air flow paths	10			
air flow pattern design	9			
cooling and	4			
global warming and	1–2			
heat loads and	5	6		
night ventilation	19	20		
purge ventilation	3			
stack effect	12			
ventilation control	33	34–35		
ventilation rates and	8	37	39	

T

Index Terms	Links		