Chapter 1
Design Procedures for Natural Ventilation

David Etheridge

Abstract The paper gives an overview of the design process for natural ventilation. It concentrates on the technical procedures that are available to the designer. The overall process is discussed in terms of four stages. For the first stage, the factors that determine the feasibility or otherwise of natural ventilation are outlined. In the second stage, the various ventilation strategies are considered. The remaining two stages involve quantitative design procedures. Prior to describing these procedures, the physical mechanisms of natural ventilation are summarised.

Keywords Natural ventilation • Design • Scale modelling • Theoretical modelling

1.1 Introduction

The aim of the first lecture is to give an overview of available procedures (experimental and theoretical) for natural ventilation design. To put these procedures into context, the whole design process is described in terms of four stages. It is not claimed that this is a definitive description nor that it is a complete one. However it is believed that it covers most of the technical issues that specifically arise with natural ventilation. It is based on the form of Chap. 4 in CIBSE (2005). There are of course other important issues that arise in practice, e.g. client acceptability, cost, detail design of components, diagnostic tools, fire safety and security. Descriptions

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Note by Author This chapter is the unchanged text of the first of four related lectures on natural ventilation, given in 2007 at the COE International Advanced School in Korea. Of the three other lectures (Etheridge 2007a, b, c), the third lecture (Etheridge 2007b) is given here as Chap. 2, again in its original form. It should be noted that a much more comprehensive and updated treatment of natural ventilation can now be found in the recent book by the author published in 2012 (Etheridge DW (2012) Natural ventilation of buildings – theory, measurement and design. Wiley, Chichester).

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of such issues can be found in publications relating to specific buildings and in more general works such as CIBSE (2005), Allard (1998) and NATVENT (1997).

1.1.1 Overall Design Process

The design of a natural ventilation system can range from a very simple process to a very complex one. The simplest procedure is to reproduce an existing design that is known to function satisfactorily under given conditions. This procedure has been followed for thousands of years and has led to the development of traditional designs adapted to specific climates. Most single-family houses are probably designed in this way. With non-residential buildings, the process is more demanding, partly because the building is likely to have some unique properties and partly because the requirements themselves are more demanding (a natural ventilation system is in competition with established mechanical systems that offer precise control over the indoor environment).

The prime advantage that natural ventilation has over mechanical ventilation is, of course, the inherently lower energy consumption arising from the absence of mechanical fans. The prime disadvantage is that, compared to mechanical ventilation, it offers less control over the indoor environment. As a result of this, a major objective of modern natural ventilation design is to improve the level of control offered by natural systems. However, the aim of the control is to ensure that the indoor conditions remain within satisfactory boundaries, rather than the very narrow range achievable with mechanical systems. It is in this area that modern technology (computational and experimental techniques) has enabled more accurate and effective designs.

The design of a naturally ventilated building can be a lengthy process involving several stages, which are likely to be iterative. There is no definitive procedure, but it is believed that dividing the process into four stages is a reasonable description, as shown in Fig. 1.1. The first stage is to assess whether natural ventilation is feasible. Here it is necessary to consider the many factors that can influence the ventilation of the building. The more important factors are briefly described in Sect. 1.2. The second stage is to choose a ventilation *strategy*, i.e. the flow pattern that is required. There may of course be more than one strategy for different times of the day or year. Ventilation strategies are dealt with in Sect. 1.3.

Having chosen the strategy, the next stage is to ensure that the airflow rates through the envelope openings and the required internal air motion can be achieved. It is here that the quantitative part of the design process really begins. It is logical to approach this in two stages. The initial quantitative design stage (stage 3 in Fig. 1.1) is where the envelope openings are designed (size and position). This is covered in Sect. 1.5. The second quantitative stage (stage 4) is where off-design investigations are carried out to gain a better idea of the overall performance of the system (Sect. 1.6). Since the technical difficulties of design arise from the complicated

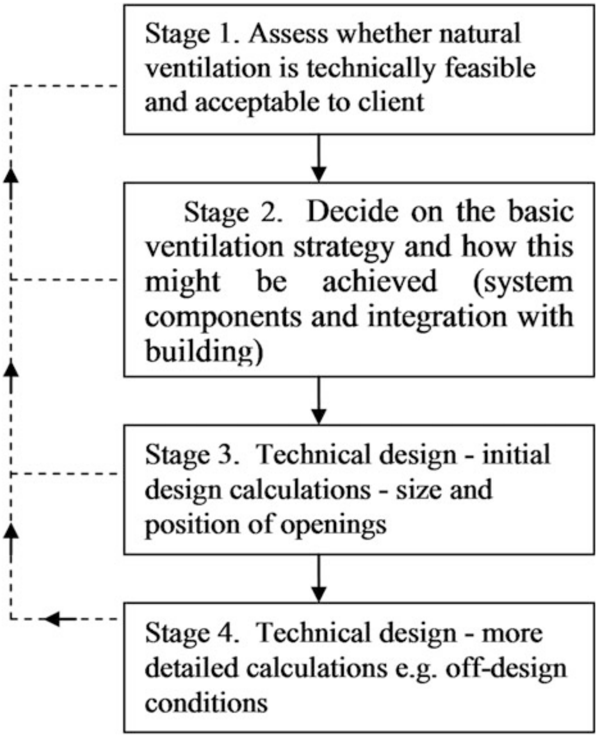

Fig. 1.1 A simplified view of stages in the overall design process

nature of ventilation flows, a brief description of the physical mechanisms is given in Sect. 1.4.

1.2 Feasibility of Natural Ventilation

1.2.1 Climate

Climate is perhaps the most important factor in deciding the feasibility of natural ventilation for non-residential buildings, partly due to variability (Fig. 1.2). The biggest challenge probably lies in hot and humid climates.

The prevention of overheating of occupants during periods of high external temperatures is a major challenge. There are basically two approaches to solving this problem. The first is the use of high ventilation rates, with the aims of (a) convective and evaporative cooling of occupants by high internal air speeds and (b) the removal of internal heat gains by the ventilation air. With high wind speeds, the aim is essentially to achieve an internal temperature that is equal to the external temperature. However high wind speeds are not guaranteed and with low wind speeds the generation of high ventilation rates requires that the internal

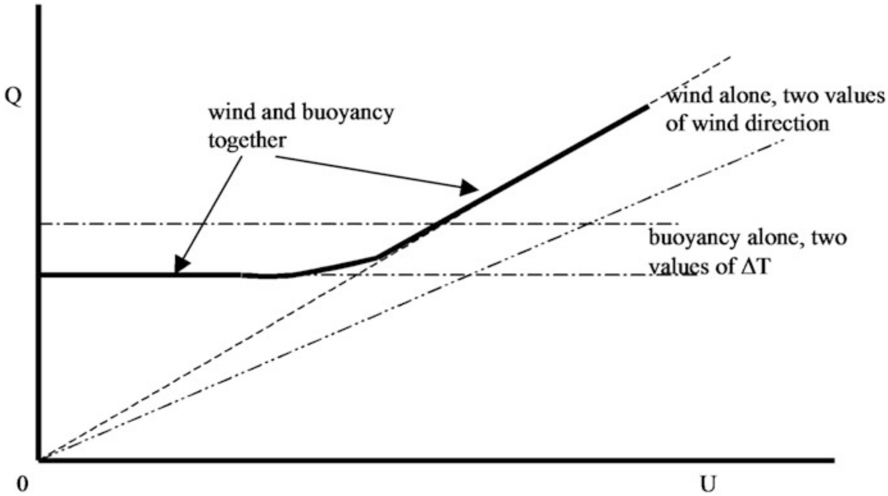

Fig. 1.2 Variability of natural ventilation rates due to climate (for fixed opening size)

temperature be higher than the external temperature by, say, 3°. This may not be acceptable when external temperatures frequently exceed 25 °C. Furthermore, large openings may not always be acceptable in commercial buildings.

The second approach is the strategy of *night cooling*. Here the aim is to cool the internal fabric of the building at night so that it can absorb internal heat gains during the day. This approach requires high ventilation rates at night and low ventilation rates during the day. A successful night cooling design can maintain the internal temperature below the external temperature (see Sect. 1.2.7) during the day, but it requires a relatively high level of control over the ventilation rates.

Perhaps the major weakness of natural ventilation is that on its own it can do little to reduce humidity levels, apart from removing moisture generated internally, e.g. by evaporative cooling of the occupants. There is no direct equivalent to night cooling. This does not mean that natural ventilation cannot be used in humid climates. It clearly can, as witnessed by domestic dwellings and by some commercial buildings (Salmon 1999).

1.2.2 Occupants

Clearly the internal environment produced by the system must be acceptable to the occupants. In fact, the success of a natural ventilation design relies on the behaviour of the occupants for several reasons. First, the occupants are assumed to modify the sizes of openings and to take other actions (e.g. use desk fans to promote cooling; reduce internal gains) in order to obtain acceptable conditions. Surveys indicate that occupants generally favour having control over their environment in this way.

Second, achievement of thermal comfort relies on the willingness of occupants to adapt actively to a changing internal environment by varying their dress and possibly their activities to achieve comfortable conditions. Furthermore, passive adaptation is important. It is increasingly being recognised that comfort criteria for air-conditioned buildings are not appropriate to naturally ventilated buildings. For example, humans adapt to their surroundings in such a way that higher internal temperatures become acceptable when the external temperature increases (Brager and de Dear 2000).

1.2.3 Building Shape and Environment

Both the shape of the building and the environment in which it is situated determine the pressures generated by the wind on the surfaces of the building and the local flow of air around the building. To some extent, the shape of the building can be specifically designed to enhance these effects (Allard 1998).

1.2.4 Building Plan and Layout

Deep plan buildings present problems for natural ventilation, because the entry of fresh air into spaces is concentrated at the external envelope. However a deep plan building can be converted into narrow plan by means of an internal courtyard or atrium, and this is a fairly common strategy to provide crossflow ventilation. High-rise buildings can be naturally ventilated by isolation (in terms of airflows) of the individual floors. There are many high-rise residential buildings that are naturally ventilated in this way. When there is a significant connection (in terms of airflow) between the various floors, the building needs to be treated as a single space. The feasibility of naturally ventilation for very tall buildings (skyscrapers) has certainly received attention (Yeang 1996; Daniels et al. 1993), but currently there are few skyscrapers that rely purely on natural ventilation.

1.2.5 Building Envelope

The building envelope is one of the most important factors in natural ventilation design. In addition to containing the openings, it can influence such factors as thermal storage (for night cooling) and internal heat gains arising from solar radiation.

A major design aim is to specify the size and position of purpose-provided openings in the envelope. Envelopes also contain adventitious openings (i.e. openings that are not purpose provided). As a general rule, the aim should be to minimise adventitious openings, and this is now recognised in many countries by the adoption of standards for adventitious leakage. In the past, much attention has been paid to the measurement and modelling of adventitious leakage (Etheridge and Sandberg 1996). One intention of standards is to eliminate the need to account for adventitious leakage. Adventitious openings can certainly be ignored when the purpose-provided openings are large, e.g. summer conditions, but they may be significant under other conditions.

1.2.6 Internal Heat Gains

Ventilation removes internal heat gains (from lighting, solar radiation, office equipment, etc.) but only at the expense of increased internal air temperature, which in summer conditions is undesirable. This means that minimising internal heat gains during the cooling season is a crucial part of a natural ventilation design. As a rough guide, the internal heat gains should be less than 30 W per m^2 of floor area. Larger values may require some form of additional cooling (passive or active).

1.2.7 Thermal Storage (Night Cooling)

The ability of the envelope of the building to store heat can have a significant influence on the temperatures experienced in a space. The heat transfer rates associated with temperature differences between the air and the fabric can be of similar magnitude to the heat transported by the ventilation air. The night cooling (night ventilation) strategy takes advantage of the thermal storage offered by the fabric of the envelope, i.e. the use of high ventilation rates at night, with the aim of removing heat from the fabric that has been gained/stored during the day. During the following day, the fabric can then absorb heat from the internal air, thereby providing passive cooling. For this strategy to be effective, it usually requires all or most of the following conditions to be satisfied:

- A large temperature swing from day to night (>10 K)
- Low internal heat gains (<30 W/m^2 floor area)
- Heavyweight construction (high thermal mass)
- High heat transfer coefficient to the internal surface
- High ventilation rates at night, low during the day

For this reason, theoretical predictions of the internal temperatures in a naturally ventilated building should include the dynamic thermal performance of the envelope. Figure 1.3a, b illustrate some of the above points using calculated results for a single office (20 m^2 floor area) with an average internal heat gain from 09.00 to 17.00 of 20 W/m^2 (i.e. a total daily gain of 3.2 kWh). The thermal mass of the surfaces has been assumed to reside in a single wall, for which the one-dimensional

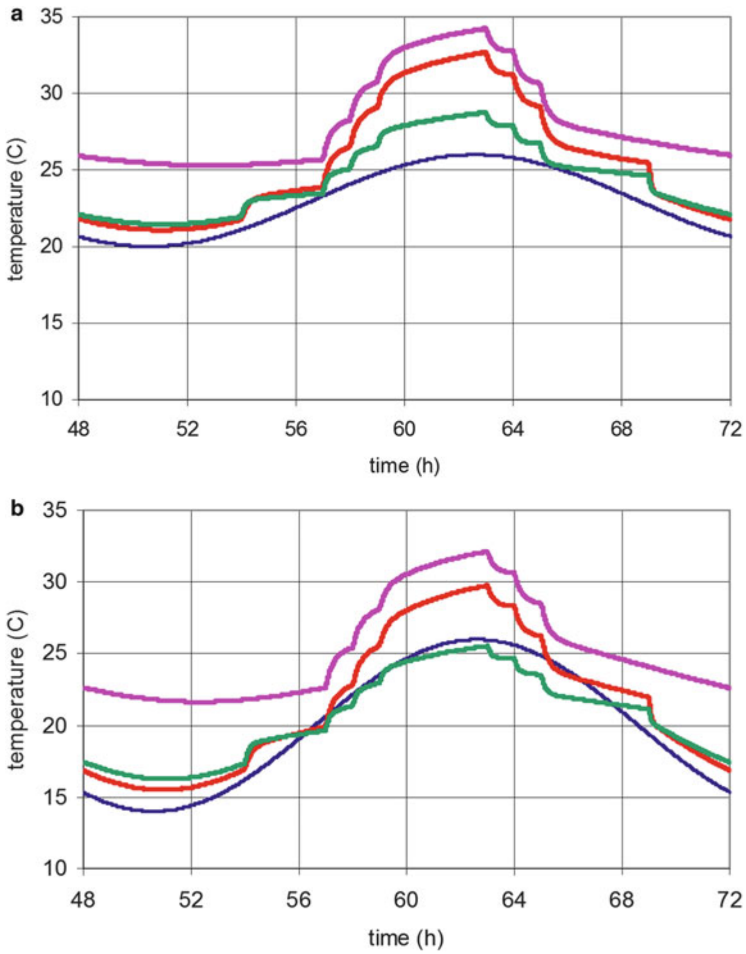

Fig. 1.3 Theoretical results for a simple building envelope, illustrating the potential for night cooling. (**a**) External temperature swing of 6 °C, (**b**) temperature swing of 12 °C

Fourier heat transfer equation has been solved. Each figure shows four curves. The lowest curve is the external temperature variation, which is sinusoidal with a peak value of 26 °C. The uppermost curve shows the internal air temperature when the ventilation rate is 1 h^{-1} at all times. The next curve shows the effect of increasing the ventilation rate to 10 h^{-1} at night for night cooling. The curve below shows the effect of doubling the thermal mass of the envelope, again with high night ventilation. Figure 1.3a is for the case of a diurnal temperature swing of 6 °C. Figure 1.3b is for a swing of 12 °C.

Modern buildings can be designed to enhance night cooling. An example is the addition of thermal mass by means of an exposed concrete ceiling to give direct thermal contact with the air. Another is the use of phase change materials to increase the storage capacity of the fabric. For both examples, the heat transfer rate between the air and the fabric is a limiting factor, and semi-active systems have been developed that use fans to increase heat transfer.

1.2.8 Control

One aim of design is to ensure that openings are sized (maximum and minimum values) so that they allow the occupants to exercise sufficient control. It is not only the magnitudes that are important. The points at which fresh air enters and stale air leaves the building are equally important. Thus a second aim of design is to ensure that the required flow pattern (the ventilation strategy) is controlled. Ideally the design should ensure that the envelope flow pattern is fixed for most weather conditions, with the magnitudes of the envelope flow rates (and internal air speeds) to be controlled by the occupants or by other devices. Air vents are available that automatically adjust their area in response to the pressures acting across them. Control can be by some form of BMS (building management system), e.g. adjustment of stack flow rates by varying the position of a damper in response to a measurement of CO_2 concentration. A system should incorporate fixed air vents to ensure that a minimum level of ventilation is always available (in some cases, adventitious openings are assumed to perform this function).

1.3 Ventilation Strategies

Ventilation strategies are described here in terms of the flow pattern that is required. Different strategies may be required at different times of the day or the year. The more common strategies are identified in the following. It is relevant to divide them into two basic categories (isolated and connected spaces).

1.3.1 Isolated Spaces

In some buildings, the spaces or rooms can be considered as isolated (in terms of airflow) from other parts of the building. For this to be true, the openings to other parts of the building must be small in relation to openings in the external envelope. Figure 1.4 illustrates such spaces and possible ventilation strategies. Spaces A and B are examples of single-sided ventilation, with a large single opening and two small openings at different heights. Spaces C and D are examples of crossflow ventilation of an isolated floor, again with large and small openings. In both cases, the flow pattern is that due to the action of wind alone. Space E shows the flow pattern due to buoyancy alone.

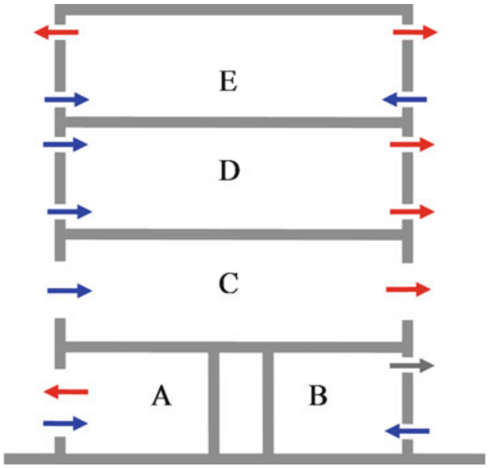

Fig. 1.4 Ventilation patterns for isolated spaces

1.3.2 Connected Spaces: Single-Cell Building

When the spaces in a building are connected by large internal openings, they effectively form a single cell, with the flow through any opening dependent on the flow through the other openings. Such spaces are relatively common in naturally ventilated buildings, partly because of the desire to minimise internal resistance to flow and partly to enhance internal mixing. Figures 1.5 and 1.6 illustrate possible strategies.

In Fig. 1.5a, an atrium is used to generate inward flow of fresh air into all of the occupied floors, i.e. crossflow ventilation of all floors. An advantage of this strategy is that wind and buoyancy can act in unison, provided the outlet opening is in a region of relatively low wind pressure and the internal temperature is higher than the external. The same effect can be obtained by means of an atrium or stairwell at one end of the building (Fig. 1.5b). A "top-down" ventilation strategy can be employed with this arrangement of openings, whereby the arrows are reversed, i.e. fresh air enters through the uppermost opening. Such a strategy may be employed when some form of cooling is provided at high level, e.g. passive downdraught cooling (Francis and Ford 1999). Wind effects are however likely to change the flow pattern.

Figure 1.6a shows the strategy where a chimney or stack is used as the outlet opening to generate fresh air entry. This is similar to Fig. 1.5b, but there is one significant difference. The chimney or stack is in the form of a duct, and the walls of the duct allow the density of air in the stack to be considerably different to that in the space, i.e. the duct walls support a large horizontal variation in density. This allows the forces generated by buoyancy to be increased, e.g. by means of a solar chimney.

Chimneys can also be used specifically to take advantage of wind forces. They are sometimes known as "windcatchers" or wind towers, and there is an interesting

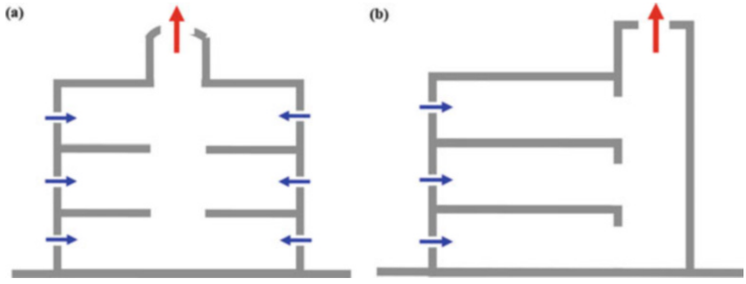

Fig. 1.5 Ventilation patterns based on atria with (a) central atrium, (b) atrium at one end

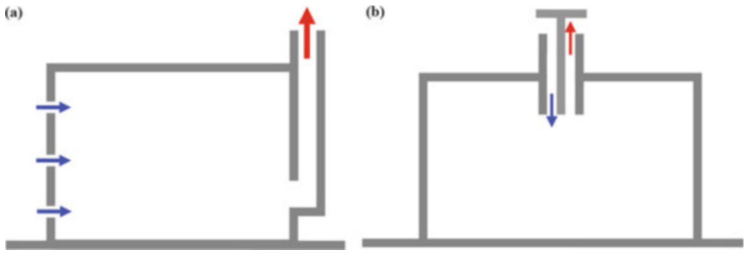

Fig. 1.6 Ventilation strategies based on chimneys (stacks) with (a) one long chimney, (b) two short ducts

variety of traditional designs, particularly in the Middle East (Battle McCarthy Consulting Engineers 1999). Sometimes two separate chimneys are used, with one acting as the inlet and one as the outlet, depending on the wind direction and provided there are no other openings. Sometimes the chimneys are placed together, as illustrated in Fig. 1.6b. The specific type shown in Fig. 1.6b has relatively short chimneys, and because of its short length, it does not protrude far into the space (the buoyancy-generated flow is however relatively low). It can be described as a balanced ventilator, since the intention is that the inlet and outlet flows are equal and this will apply for any wind direction.

1.3.3 Connected Spaces: Multicell Building

When the openings between spaces are neither large nor small compared to the openings in the external envelope, the building can be described as multicell. This description arises from envelope flow modelling. In terms of envelope flow pattern, there may be no difference to the single-cell equivalent.

1.4 Mechanisms: Physical Descriptions

The ventilation of a building can be considered as comprising two processes:

- Envelope flow – the entry and exit of air through openings in the building envelope
- Internal air movement – the motion of the air whilst it is inside the envelope

Internal air motion is of importance, primarily because of its direct influence on the well-being of the occupants (thermal comfort, air quality). With natural ventilation, the internal air movement can have a direct effect on the envelope flows, and by virtue of the fact, it plays a role in determining the temperature (density) distribution within the space and hence the pressure differences across the openings. Thus the two processes are not independent, but the dependence is not always very strong, and in design, it is not uncommon to treat them separately. This is justifiable in the early stages of design, because of the considerable simplifications it offers. The following physical descriptions are for three different conditions, namely, buoyancy alone, wind alone and buoyancy and wind combined. Attention is focused on the difficulties that arise with theoretical modelling and scale modelling.

1.4.1 Buoyancy Alone (No Wind)

In the absence of wind (still-air conditions), the envelope flows are generated by buoyancy, i.e. gravity acting on density differences. If we consider the building shown in Fig. 1.5a, for example, the external air pressure variation is given by the hydrostatic equation, i.e. a linear decrease of pressure P_E (Pa) with height z (m).

When the air inside the building is not in motion, the hydrostatic equation again applies, so the internal surface pressure, P_I, decreases linearly with z (when the internal density is uniform) but at a different rate. At a given height, it can be seen that P_I and P_E are not in general equal, i.e. a pressure difference will be generated across the envelope, and where there is an opening, a flow occurs.

Inside the space, there will be air motion, arising partly from the momentum of the air flowing through the openings and partly due to buoyancy forces. The latter arise primarily from heat transfer into and out of the air at surfaces. Common sources of heat transfer are conduction from the surfaces of the envelope, from heating or cooling appliances, from lighting and from the occupants. These can lead to identifiable convective streams known as plumes. The flow of air in the plumes is usually turbulent. Dry air is transparent to thermal radiation, but radiation still plays a role in the sense that it affects the surface temperatures of the envelope. The fact that surface heat transfer plays a major role in determining the internal air motion leads to major problems in both theoretical and experimental modelling, as discussed in Sect. 1.6.3 and Etheridge (2007b).

Variations of internal density with height (stratification) can be expected, particularly in tall spaces, such as atria, where the temperature at high level is often greater than the temperature at low level. A decrease of density with height often leads to stable stratification, whereas the introduction of dense air at high levels can lead to instabilities, typified by low-frequency unsteadiness. In some cases, negative buoyancy can occur, e.g. when night cooling is employed. In the so-called top-down ventilation system, pre-cooled (and denser) air at high level is induced to flow downwards, thereby providing cooler air at low levels.

The internal velocities generated by buoyancy are often small compared to the velocities of the air through openings, and when this is the case, the internal pressure can be taken as given by the hydrostatic equation. This assumption is made in envelope flow models. A related assumption is that density gradients in the horizontal directions are small, i.e. density varies only in the vertical direction.

1.4.2 Wind Alone (Uniform Density)

With wind alone, the pressure differences across the envelope arise as a result of the changes in velocity that occur as the airflows around the building. The airflow is invariably turbulent, due partly to the turbulence in the upstream flow and partly to flow separations on the building itself.

The fact that the external pressure field is fluctuating means that the flows through the openings will be unsteady, whereas, with buoyancy alone, they are inherently steady. In addition, the velocity conditions at the inlet (or outlet) of an opening can influence the flow characteristic of the opening. A further complication arises when an opening is large in relation to surface in which it lies, when it can affect the flow over the external surface and the external pressure distribution. These effects are difficult to model theoretically, but they present less of a challenge to scale modelling. Small openings are easier to model theoretically and a relatively simple type of model (envelope flow model; see Etheridge (2007b)) can be used. With such openings, the external airflow can be considered as independent of the openings. Furthermore, the internal velocities generated by flow through the openings are small, and the internal conditions are therefore close to those in a laboratory test where the discharge coefficient of the opening can be determined. Both of these features mean that each opening can be treated in the model as a separate entity.

With large openings, the internal motion will be turbulent (characterised by nominally random fluctuations in velocity and pressure throughout the space) with similar velocities to those through the opening. The underlying problem in modelling wind-alone conditions is the presence of turbulence (external and internal). The absence of buoyancy makes scale modelling less difficult, and environmental wind tunnel techniques have been developed that allow useful results to be obtained (see Etheridge (2007a)). Theoretical modelling is also less difficult and the modelling of turbulence is becoming increasingly more realistic.

1.4.3 Wind and Buoyancy Combined

In the general case, buoyancy and wind act simultaneously, and when the two effects are of similar magnitude, the difficulties of theoretical and scale modelling are at their most severe.

1.4.4 Flow Through Openings

1.4.4.1 Types of Opening

The flow characteristic of an opening is determined partly by its geometry (shape and size) and partly by the conditions surrounding the inlet and the outlet. Openings in envelopes fall into two categories, i.e. purpose-provided and adventitious openings. Purpose-provided openings are intentional openings, such as vents, open windows and stacks. A major objective of design is to determine the size (maximum and minimum values) and position of these openings. Adventitious openings are unintentional openings, such as gaps and cracks in walls, doors and windows. Adventitious openings are simply all those openings that are not purpose provided. It is probably impossible to construct a building envelope that is completely airtight. However, excessive adventitious leakage is undesirable if the system is to operate satisfactorily in winter conditions. Under these conditions, the purpose-provided openings will be small, to minimise heat loss, so adventitious openings may be significant. Adventitious openings can be taken account of in the design, although their effect may be the source of considerable uncertainty. With the larger openings associated with summer (cooling) conditions, adventitious leakage can be neglected.

For the purpose of this lecture and its companions, it is convenient to divide purpose-provided openings into the three types shown in Table 1.1. Adventitious openings are the fourth type.

Type 1, 2 and 3 openings are distinguished by their size and shape and the consequential flow characteristics. In Table 1.1, L/d denotes the length-to-diameter ratio and A_{op}/A_w denotes the ratio of opening area to the area of the wall in which it lies. Type 1 openings have low values for both these ratios (NB; the values quoted are only a very rough guide). The low L/d means that the discharge characteristic, C_d, of the opening can usually be treated as a constant. The low area ratio means that the presence of the opening only has a local effect on the pressure distribution generated by the wind on the wall. It also means that flow through the opening will be unidirectional. These features make such openings particularly amenable to treatment in theoretical envelope flow models.

Type 2 openings are long openings such as chimneys and stacks, with L/d typically greater than 5. This means that the discharge coefficient will vary with flow rate. However, it also means that the flow will be unidirectional, so treatment

Table 1.1 Types of envelope openings

Type	Description	Area ratio	L/d	Characteristics	Flow type	Examples
1	Purpose-provided opening: small and short	<0.1	<2	C_d = constant	Unidirectional flow	Vents, small window
2	Purpose-provided opening: long	<0.1	>5	C_d depends on *Re*	Unidirectional flow	Chimneys
3	Purpose-provided opening: large and short	>0.2	<2	C_d = constant with unidirectional flow	Bidirectional flow possible	Large open windows
4	Adventitious	–	–	C_d depends on *Re*	Unidirectional flow	Cracks in door and window frames

in an envelope flow model is not too difficult. Type 3 openings, such as large window openings, present the greatest difficulty, due to the large area ratio. This means that bidirectional flow can occur in the presence of wind and buoyancy. Furthermore, they may be large enough to influence the surface pressure distribution and may interact strongly with the local turbulence velocity field. Although the discharge coefficient is likely to be independent of flow rate, when determined in a laboratory, the use of this C_d to describe the flow characteristic becomes questionable.

The above comments relate to theoretical modelling of the openings. When scale modelling is concerned, the key characteristic is whether C_d is dependent on flow rate, so that type 2 openings present the major difficulty (see Etheridge (2007a)). Adventitious (type 4) openings are often unidentifiable and they often have small dimensions. They can be dealt with theoretically but only by making some broad assumptions. It is virtually impossible to include them in scale modelling.

1.4.4.2 Flow Characteristics

The steady flow characteristics of purpose-provided openings with unidirectional flow can be measured in a laboratory test rig (under still-air conditions) by subjecting the opening to a known and steady pressure difference and measuring the resulting flow rate. The flow characteristic can then be conveniently expressed in terms of a discharge coefficient C_d:

$$C_d \equiv \frac{q}{A}\sqrt{\frac{\rho}{2\Delta p}} \tag{1.1}$$

where Δp denotes a defined pressure difference across the opening (Pa), ρ the density of the inflowing air (kg/m^3), A a defined area(m^2) of the opening and q the volume flow rate (m^3/s). In general, C_d will vary with flow rate (Reynolds number

Re). However, for type 1 and type 3 openings, where the flow is dominated by flow separation at sharp edges, the discharge coefficient will be found to be virtually constant above a certain flow rate. This fact is of special importance to scale modelling (Etheridge 2007a), and it also simplifies theoretical calculations.

When the opening is situated in a turbulent flow field (fluctuations of pressure and local velocity), the concept of the discharge coefficient becomes increasingly less tenable as the time-averaged pressure difference across the opening approaches zero. An extreme example of this occurs when the mean pressure difference across the opening is equal to zero, as can arise with a single opening in an otherwise sealed room. Here the ventilation rate becomes independent of the area of the opening, since inward and outward flow is determined by the compressibility of the air in the space. When there is more than one opening, turbulent diffusion by the velocities becomes important. Early work on these and related issues is discussed in Sect. 3.2 of Etheridge and Sandberg (1996).

1.4.5 Mathematical Models

The fundamental equations that govern air motion are the unsteady Navier-Stokes equations (obtained by applying Newton's second law to the motion of a small element surrounding a point in the flow), the corresponding equations for conservation of energy (kinetic and thermal) and mass and the thermodynamic equations of state. Numerical techniques for solving certain forms of these equations have been developed and are generically known as computational fluid dynamics (CFD) (see Sect. 1.6.3). Steady flow is commonly assumed, although unsteady flows can be dealt with.

Another type of model that is commonly used in ventilation design is the envelope flow model. This type is much simpler. It calculates the flow rates through the openings using equations derived from integration of the fundamental equations over large volumes. The internal density (temperature) distribution has to be specified, along with the external wind pressure distribution and the flow characteristics of the openings. Thus the simplicity of the equations is accompanied by a need for empirical data, which may be difficult to obtain. This type is discussed briefly in Sect. 1.6.1 and in detail in Etheridge (2007b). Again, steady flow is commonly assumed, but unsteady models have been developed.

The other type of model in common use is that which combines a model of the thermal behaviour of the envelope with an airflow model. This type is briefly discussed in Sect. 1.6.4. These models by their very nature are unsteady models, but the timescales involved are relatively large (of order 1 h), since the intention is to model the thermal behaviour of the envelope, rather than the effects of wind turbulence.

1.5 Initial Design Process: Size and Position of Openings

Here we are concerned with stage 3 of the design process (see Fig. 1.1). For the chosen strategy (flow pattern), the initial design aim is to determine the sizes (and positions) of openings required to give the required flow rates (magnitudes). This can be done using an envelope flow model in what is known as the explicit method, and the procedure is described in detail in Etheridge (2007b). The starting point is, where relevant, to divide the spaces in the building into two types, i.e. spaces which are isolated and spaces which are connected. As noted earlier, a room or space can be considered as isolated when the openings connecting it to the remainder of the building are very small in relation to the openings in its external envelope. Figure 1.4 shows some examples. Spaces with relatively large openings between them can be considered as connected, in the sense that there is negligible pressure difference between them. In these cases, it is necessary to consider all of the spaces simultaneously when calculating ventilation rates. If the building contains both isolated and connected spaces, they can be treated separately. If the openings connecting the spaces are of similar size to the other envelope openings, it is possible to make use of a multicell envelope flow model. However this cannot be solved in an explicit manner.

1.5.1 Design Conditions

In a climate where there are two distinct seasons that require respectively heating and cooling, two basic design conditions exist. One determines the minimum sizes of the openings and the other determines the maximum sizes. By determining the maximum and minimum openings, the occupants (or other control systems) should be able to exercise the control to satisfy most weather conditions throughout the year. There may of course be other design conditions for which the explicit method is applied; e.g. with night cooling large openings may be required at night and small openings during the day. However, here we consider the two basic conditions.

Ventilation is required to provide satisfactory indoor air quality and it plays a role in satisfying thermal comfort. In an office, the required fresh air rate for air quality will lie in the range from 5 to 8 l/s per person, corresponding, respectively, to control of CO_2 and body odours. From this, it is relatively easy to specify the required envelope flow rates. It is more difficult to specify flow rates required for thermal comfort, partly because the internal temperatures will depend on the dynamic thermal behaviour of the building and partly because the occupants can be assumed to be adaptable.

1.5.1.1 Winter (Heating Season)

A common aim of the winter design condition is to ensure adequate indoor air quality under most conditions, without excessive heat loss due to ventilation. This is not as straightforward as it sounds and there is a degree of choice for the designer. The basic procedure consists of the following steps:

(i) Determine the minimum ventilation rates required for air quality.
(ii) Decide the "worst-case" condition (wind speed, direction and temperatures).
(iii) Use the explicit method to calculate the open areas required for this condition.
(iv) Select appropriate openings.

The areas obtained are basically the minimum sizes for the openings, i.e. the type of openings should be chosen such that this area is permanently available.

The choice of the "worst-case" condition in step (ii) is not clearly defined. The choice should usually correspond to a high ventilation rate; e.g. the designer might choose the weather conditions for which there is only a 1 in 10 chance of them being exceeded. With less extreme conditions, the occupants will be assumed to increase the openings as appropriate. For step (iii), it is preferable to make use of adjustable vents, rather than openable windows. Windows are not ideal for achieving small openings and the coarse control could lead to excessive ventilation.

1.5.1.2 Summer (Cooling Season)

The ventilation rate required to prevent overheating will usually exceed that required for air quality. Thus the first step is to decide the cooling strategy that one wishes to adopt (see Sect. 1.2.1). In climates where the external temperature rarely exceeds 25 °C, the aim may be to achieve high ventilation rates when there is little wind, by allowing the internal temperature to exceed the external temperature by a small amount. For this case, the basic procedure consists of the following steps:

(i) Decide the acceptable peak temperature rise, e.g. 3°.
(ii) Calculate the ventilation rate required to ensure that this temperature rise is not exceeded.
(iii) Take "worst case" to be zero wind speed.
(iv) Calculate the open areas required and design the openable windows such that this maximum value can be achieved.

The magnitude of the acceptable temperature rise in step (i) should lie within agreed comfort criteria. For step (ii), the calculations should ideally include the thermal characteristics of the building, i.e. a full thermal response calculation over a period of several days. Figure 1.3 is an example of such a simulation. In some circumstances, a simple calculation that ignores thermal storage may suffice, i.e. the required ventilation rate is calculated on the assumption that ventilation directly removes all of the internal heat gains.

1.6 Later Design Process

Here we are concerned with stage 4 in Fig. 1.1. This stage is likely to be more demanding in terms of resources than stage 3. For example, once initial sizing has been done, the designer may wish to examine off-design conditions with these openings and to determine more details of the flows and temperatures inside the building. On the basis of these results, the initial sizing calculations may be reconsidered.

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

- Scale modelling
- Envelope flow models
- Computational fluid dynamics or CFD
- Combined thermal and airflow models

1.6.1 Scale Modelling

Scale modelling is the subject of Etheridge (2007a). It will be seen that scale modelling is particularly useful for the wind-alone case, primarily because wind tunnel techniques allow relatively accurate modelling of turbulence. Wind tunnel testing is currently the main source of information on wind pressure distributions. Wind tunnels can also be used for measuring directly the ventilation rate of a building and the internal air motion and for investigating the flow characteristics of certain types of opening. These latter uses are however limited by the size of the building model that can be used.

The presence of buoyancy (with wind) imposes severe limitations on scale modelling in wind tunnels, but it is possible to determine ventilation rates. Internal air motion is virtually impossible to deal with. However, scale modelling using liquids rather than air offers some possibilities, particularly for the buoyancy-alone case.

1.6.2 Envelope Flow Models

Envelope flow models are the subject of Etheridge (2007b). As noted earlier, they can be solved in an explicit manner, where the flow rates are specified for given weather conditions and the areas are calculated. More generally, they can also be solved in an implicit manner, where the opening areas are specified and the flow rates are calculated.

Implicit solutions are useful for looking at off-design conditions. Multicell 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. Some multicell models include equations for predicting pollution concentrations. Multicell models can also form part of a combined thermal and flow model. Zonal models are a step further than multicell models, in that the rooms are further divided into a number of zones. Envelope flow models have the advantage that they can be used for assessing the influence of adventitious leakage.

A disadvantage of envelope flow models is that they ignore any interaction between the internal flow and the envelope flow; e.g. the internal density distribution usually has to be specified. It is also difficult to deal with large openings, and the discharge coefficients of the openings have to be specified. The main advantage lies in their simplicity and speed of use. It is also possible to deal with unsteady wind effects, although this requires knowledge of the unsteady wind pressures.

1.6.3 Computational Fluid Dynamics (CFD)

CFD is perhaps the most detailed and potentially the most versatile of all design procedures for ventilation. It can be extended by adding further equations and empiricisms to predict such things as pollutant concentrations, ventilation efficiency and the spread of fires. Here we are only concerned with an overview of CFD and its limitations compared to other procedures.

The term CFD refers to numerical solution of the partial differential equations governing a flow field, such that the velocities, temperatures and pressures at all points in the field are predicted (Etheridge and Sandberg 1996; Blazek 2001; Awbi 1991). For the wind-alone case, the governing equations are the unsteady Navier-Stokes equations (momentum) and conservation of mass. Most CFD models use a time-averaged form of the momentum equation, with semiempirical equations for the turbulent shear stresses. These are known as RANS models. Direct numerical solution (DNS) of the equations is possible, but it is not currently feasible for design purposes. LES (large eddy simulation) lies somewhere between RANS and DNS models and is being increasingly applied to ventilation problems. In the LES model, the larger turbulent eddies are directly modelled, and as a consequence, the turbulent fluctuations are predicted. The inclusion of buoyancy requires simultaneous solution of the thermal energy equation and equations of state. Most CFD models have this capability.

The applications of CFD of prime interest to the design of naturally ventilated buildings include:

(a) Internal flows – calculation of velocity and temperature fields in spaces with specified boundary conditions at the envelope

(b) External flows – calculation of airflow around buildings and surface wind pressure distributions
(c) Whole-field calculations, i.e. the combination of (a) and (b)
(d) Component flows – calculation of flow through components, e.g. discharge coefficients of chimneys

Of these, (a) is currently the most used in design, because it provides a means of determining internal air motion and temperatures which are very difficult to obtain in other ways. However it does require specification of difficult boundary conditions. Applications (b), (c) and (d) are used but not to the same extent.

1.6.3.1 CFD Software

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

(i) The preprocessor, where the user sets the boundary conditions for the solution, including the specification 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 whole-field calculations. For the latter type of calculation, it is necessary to model the upstream and downstream flows, the flows through the openings and the internal flow. This requires a high concentration of cells in and around openings. Figure 1.7 from Yang (2004) indicates the large number of cells required for the relatively simple case of an isolated building with two openings.
(ii) The 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 predefined limits. Solution times can vary from a few hours to several days, depending on the complexity of the problem. The user has to assess whether convergence has been satisfactorily achieved.

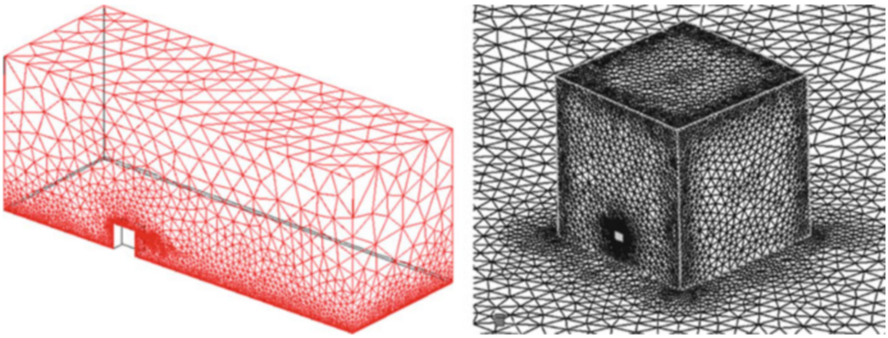

Fig. 1.7 Example of cell distribution for a whole-field calculation of a simple building with two openings (Yang (2004))

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.

(iii) The post-processor, where the results are presented in a suitable form.

1.6.3.2 Uncertainties in CFD

CFD is a powerful design tool, in the sense that very complicated flow situations can be modelled. However it is important to appreciate that the solutions obtained are subject to uncertainties as with any modelling procedure. Three sources of uncertainty are briefly discussed in the following:

(a) Calculation grid. The results should be independent of the chosen grid and the number of cells. This source of uncertainty should eventually be largely eliminated by the development of more powerful computers.

(b) 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.

Figure 1.8 (Yang 2004) is an example of the prediction of wind pressures on a simple cuboid building. Full-scale measurements are shown by the solid points. The precise details are not relevant here, but the figure illustrates the uncertainties that

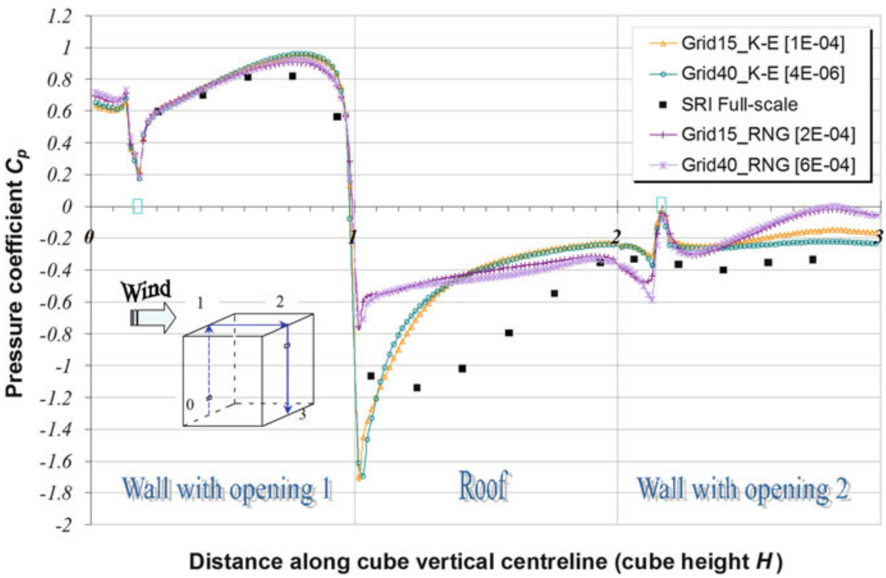

Fig. 1.8 CFD predictions of surface pressure distributions with two turbulence models (From Yang (2004))

can occur with different turbulence models. Turbulence models are still the subject of considerable research and development, and one can expect the uncertainties associated with them to reduce.

(c) Boundary conditions. A real flow satisfies certain conditions at its boundaries and develops with time from an initial condition. However, the majority of CFD calculations ignore the development with time and predict a steady-state solution for given steady boundary conditions. There are at least two sources of uncertainty with this steady approach. First, it is assumed that the steady state is independent of the initial boundary conditions. This is a questionable assumption, particularly when buoyancy is involved. Even with envelope flow models, multiple solutions can occur. Second, there will be uncertainties in the specification of the steady boundary conditions. The first source can in principle be overcome by carrying out an unsteady calculation from an initial boundary condition, but this is a lengthy process. There also remains the fundamental issue that the manner in which the numerical procedure reaches a converged solution is iterative, and this is not the same as the physical process. In some cases, a converged solution may not be obtained. These problems seem to be more prevalent when buoyancy is involved, and this may reflect instabilities in the motion that physically occur. More information on such problems can be found in the Chartered Institution of Building Services Engineers (2005), Etheridge and Sandberg (1996) and Orme (1999).

The value of detailed CFD solutions can be undermined if the boundary conditions are uncertain and the detail is sensitive to the conditions. Steady boundary conditions for velocity are easy to specify in some respects, but thermal boundary conditions at surfaces are more difficult. Unsteady boundary conditions, such as are required with LES models, are difficult to specify. In the long term, when numerical methods and turbulence models have further advanced, the uncertainties of CFD solutions may be determined mainly by the accuracy with which the boundary conditions can be specified.

1.6.4 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.

By combining a ventilation model (envelope flow or CFD) with a thermal model, this difficulty can in principle be overcome, although it still represents a challenge. Ideally the two models would be completely integrated, such that the governing equations are solved simultaneously. A simpler approach is to solve the two models separately, with some form of link between their solutions. Examples of such approaches and the problems encountered can be found in CIBSE (2005) and Allard (1998).

1.7 Conclusions

The overall design process can be described in terms of four stages. In the first stage, the feasibility of natural ventilation is assessed. The greatest challenge is likely to be the cooling season. Here it is necessary to reduce internal heat gains. The thermal characteristics of the envelope are also important, as are the ability and willingness of occupants to adapt to relatively high internal temperatures. Night cooling can play an important role.

In the second stage, the ventilation strategy (or strategies) are decided. The choice of strategy (flow pattern) will depend on the purpose of the building and its layout.

The aim of the third stage is to determine the size and positions of the openings that will give the required flow pattern (strategy) and the required envelope flow rates under specified conditions. The maximum and minimum sizes of openings that will allow the occupants to exercise control over the system are determined. Envelope flow models, solved in an explicit manner, are suitable for this purpose.

The fourth and final stage consists of more detailed and wider examination of the design, based on the results of the third stage. The greatest challenge lies in the determination of internal air motion and temperatures in the presence of both wind and buoyancy. Potentially the most versatile design tool at this stage is CFD. However, the use of CFD for certain conditions (e.g. whole-field calculations) is far from routine and is still subject to considerable difficulties and uncertainties. Ultimately the performance of CFD is likely to be limited by the uncertainties present in the specification of boundary conditions. Envelope flow models have a role to play in this stage, partly because of their ease of use and partly because they can be combined with dynamic thermal simulation models. Scale modelling also has potential, particularly for the wind-alone case, where environmental wind tunnels offer realistic turbulence simulation.

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