CHAPTER 15

Passive Solar and Low Energy Building Design

This chapter deals with the use of passive techniques to control the environment within buildings. Through the use of passive solar strategies it is possible to produce an architecture which relies more on the building envelope, and less on the use of mechanical equipment as the primary climate modifier. In particular, the impact of passive environmental control strategies on the design and operation of buildings is discussed.

15.1 Introduction

Strictly speaking, the term *passive solar* refers to the harnessing of the sun's energy to heat, cool, ventilate and illuminate buildings without the use of mechanical equipment. As with so many artificial classifications it has become somewhat corrupted and now is a generic term for a design philosophy which seeks to produce low energy buildings which are sympathetic to the natural environment. A better term might therefore be *climate sympathetic architecture*, since buildings created by this design philosophy use their envelope as the primary climate modifier and relegate any mechanical plant that is required to a supplementary role. This is in contrast to the twentieth-century practice of erecting buildings with unsympathetic envelopes, thus creating a hostile internal environment, which can only be rectified by the use of extensive mechanical services. While the precise definition of the term *passive solar architecture* may be arguable, there is no doubt that its central aim is to produce low energy buildings which utilize relatively simple technologies. In such buildings the emphasis is on the envelope, with the result that passive solar buildings tend to have complex façades, which incorporate features such as external shading, opening windows and light shelves.

While it may be possible in certain applications and in some locations to rely totally on the sun's energy to provide a comfortable internal environment, in most passive solar buildings some mechanical plant is still required. This mechanical plant can be used either:

- to supplement the passive technologies as a secondary climate modifier or
- as a facilitator, which enables the passive technologies to perform in an optimum manner.

Most passive solar buildings are therefore in reality hybrids in which passive technologies are used in tandem with mechanical equipment to achieve a low energy solution. In recognition of this fact, a new term *mixed-mode* has come into being. Mixed-mode buildings are so called because they use a combination of natural ventilation and mechanical ventilation to achieve the desired cooling effect [1]. Mixed-mode strategies tend to provide solutions which are more flexible than those produced by pure passive strategies. They are therefore more suitable for use in speculative buildings where the final use of the building may not be known at the design stage.

Because passive solar buildings contain fewer moving parts compared with their mechanical counterparts, it is tempting to believe that *passive* buildings are simpler and easier to design. In fact nothing could be further from the truth. To create a good *passive* building, the designer must have a comprehensive knowledge and understanding of heat transfer and fluid mechanics. Unlike *mechanical* buildings, which use known and easily quantifiable system drivers such as boilers and fans, *passive* buildings use natural 'variables' as drivers, such as solar radiation and wind. This means that considerable analysis must be undertaken at the design stage to ensure that a robust design is produced (i.e. one which operates well under various meteorological conditions). If this is not done, considerable problems can arise and costly mistakes can be made. For example, a building heated purely by solar energy may become uncomfortably cool on days when there is heavy cloud. One major problem for designers is to predict, at the design stage, how passively controlled buildings will behave in practice. Failure to predict performance at the design stage can be a recipe for disaster. Therefore great care must be taken at the design stage. To assist in the design of passive buildings, engineers often use complex and powerful tools such as *computational fluid dynamics* (CFD) to predict accurately how such buildings will perform. However, the costs involved in using CFD are high and expertise is scarce. Indeed, in some applications the high cost of CFD analysis and the general lack of expertise in this field are major obstacles to the use of *passive techniques*.

15.2 Passive Solar Heating

Solar energy is the radiant heat source upon which all life ultimately depends. It is in plentiful supply, even in relatively northerly latitudes. Consider, for example, latitudes

45° north and 45° south (i.e. the respective latitudes of Minneapolis in the USA and Dunedin in New Zealand). At these latitudes the noontime solar intensity in mid-winter on south-facing vertical glazing is 595 W/m^2 [2]. Given that most of the Earth's population lives between these latitudes, it becomes clear that there is great world-wide potential for harnessing solar energy.

Passive solar heating techniques are particularly well suited to applications which experience both low winter air temperatures and clear skies. Under these conditions the abundant solar radiation available during the daytime can be collected and stored for use at night-time when heat is most required. Passive solar heating techniques have been successfully applied in North America on many small- and medium-sized buildings [3]. The headquarters building of the Rocky Mountain Institute in Colorado, USA, uses solar energy to provide its heating and hot water needs. Through the use of solar energy and a highly insulated envelope, the building manages to maintain an acceptable internal environment with virtually no conventional heating, despite experiencing outside air temperatures as low as 40°C [4]. Passive solar heating techniques have also been applied successfully in more northerly and cloudier climates. For example, St George's School in Wallasey, constructed in 1961, is an early example of one such building in the UK [4]. However, it is true to say that it is more difficult to utilize solar energy in the temperate and cloudy climates of northern Europe than it is in more southerly climates.

There are four basic approaches to passive solar heating: *direct gain* systems; *indirect gain* systems; *isolated gain* systems and *thermosiphon* systems [5,6]. All four techniques aim to store, in various ways, solar energy during the daytime for use at night-time when outside air temperatures are low. They all involve the use of high mass materials in the building fabric to store heat. In the *direct gain* system, solar radiation enters room spaces directly through large areas of south-facing glazing. In the *indirect gain* system, the solar radiation is intercepted by a high mass thermal storage element, which separates the room space from the south-facing glazing. The *isolated gain* system is a hybrid of the first two systems, which uses a separate sun space, such as a conservatory or atrium, to capture the solar energy. Finally, *thermosiphons* can be used to promote movement of warm air around buildings.

All solar heating systems rely on the use of large glazed areas to catch the sun's radiation. Glass transmits relatively short-wave solar radiation in the wavelength range 380–2500 nm, but blocks radiation at wavelengths exceeding 2500 nm. Although glass permits solar radiation to enter room spaces, it blocks much of the long-wave radiation which is emitted when the surfaces in the room become hot. This phenomenon is known as the *greenhouse effect* (which should not to be confused with the *greenhouse effect* associated with global warming) and it leads to heat build-up within room spaces. Due to the *greenhouse effect*, the temperature within room spaces rises until the heat losses by conduction and convection equal the heat gains by radiation.

As well as promoting the greenhouse effect within buildings, glazing also plays an important role in the self-regulation of solar heat gains. Glass transmits much more solar radiation when the angle of incidence is small, compared with when it is large. When the angle of incidence is large much of the incident solar radiation is reflected. This quality can be used to great effect by building designers. Consider the simple building shown

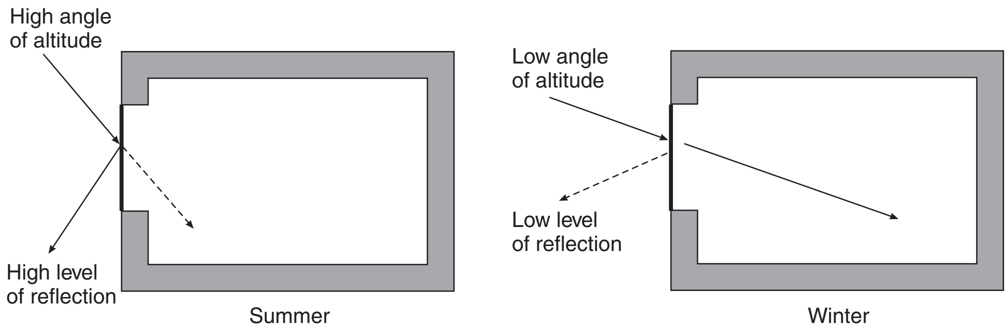

FIG 15.1 Solar reflection from glazing.

in Figure 15.1. In winter, when solar heat gains are most advantageous, the sun is low in the sky and the angle of incidence on the vertical glazing is small. This maximizes the solar transmission through the glass so that the sun's rays penetrate deep into the room space. Conversely, in summer, when solar heat gains are undesirable, the sun is high in the sky and the angle of incidence on the vertical glazing is large, with the result that much of the solar radiation is reflected. In addition, because the sun's angle of altitude is much higher in summer, vertical windows present a much smaller 'apparent' area to solar radiation in summer compared with winter (see Figure 15.2). As a result the solar intensity on vertical glazing is often much lower in summer than in winter. It should be noted that if horizontal roof lights are used the situation is reversed with the greatest solar heat gains being experienced during the summer months.

Most solar heating techniques rely on high mass materials to store heat. A variety of materials can be used to store solar energy; concrete, masonry blocks, water tanks and even rocks have all been used to fulfil this thermal storage role. Essentially, any material which has a high specific heat capacity and is a good conductor of heat can be used in this role.

15.2.1 Direct Gain Techniques

The utilization of direct solar gains is probably the simplest approach to passive solar heating. It involves using the actual living space within a building as the solar collector (as shown in Figure 15.3). To maximize the amount of solar radiation collected during the winter months, rooms should have large areas of south-facing glazing. Floors and walls of the rooms should be constructed from dense materials with a high thermal storage capacity. During the daytime, short-wave radiation is absorbed by the exposed high mass interior, while in the evening and at night-time heat is transferred from the warm room surfaces to the occupants and the air by radiation and convection. As well as facilitating thermal storage, during the daytime the exposed thermal mass absorbs heat and thus tempers the internal environment, so that overheating is prevented. In order to prevent conduction of the heat away from the high mass storage material, insulation material should always be placed between the dense interior and the outside. Although it is usual to use concrete or masonry blocks to achieve the thermal mass, it is possible to use water containers inside the building to store heat. However, these tend to be difficult to integrate into the overall building design.

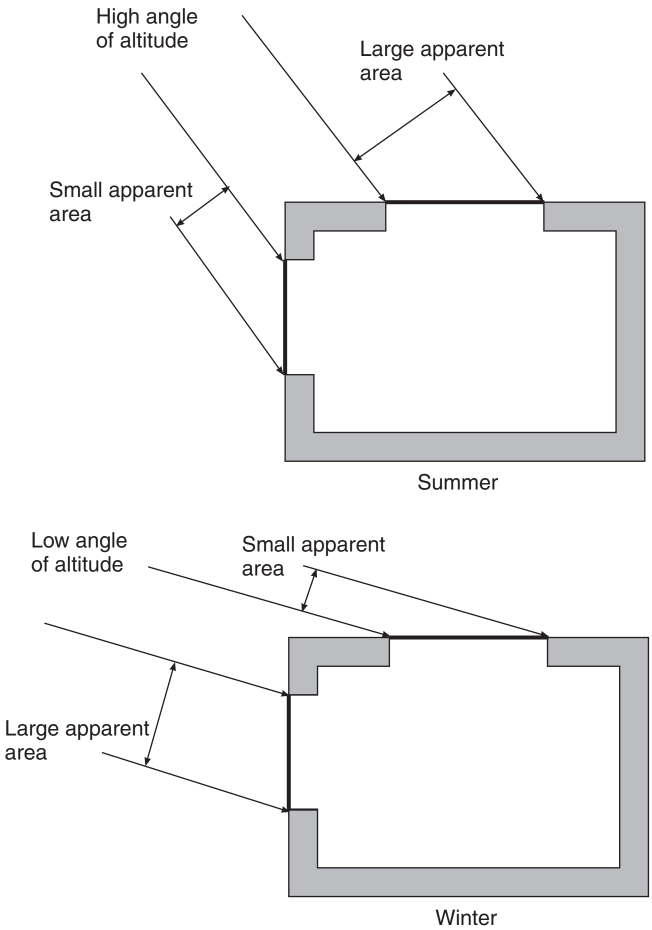

FIG 15.2 Solar angle and apparent area.

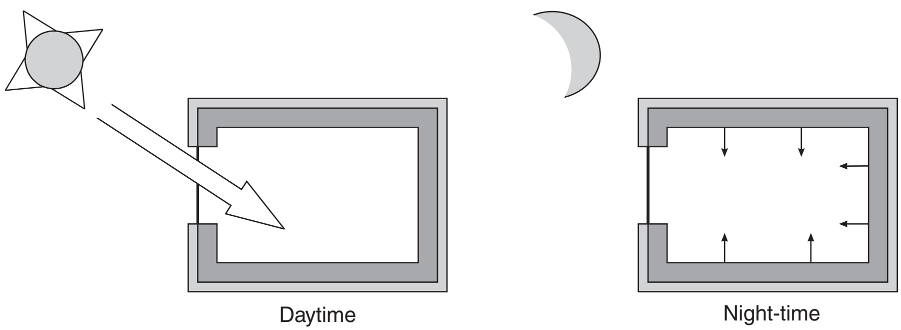

FIG 15.3 Direct gain solar heating.

15.2.2 Indirect Gain Techniques

In an *indirect gain* system, an element with high thermal mass is situated between the sun and the room space. Any solar energy striking the thermal mass is absorbed so that it heats up during the daytime. In the evening and at night-time heat is transferred to the rooms from the thermal mass by a combination of conduction, convection and radiation. Figure 15.4 illustrates the operation of one such indirect system, the Trombe wall, which comprises a masonry wall up to 600 mm thick, located directly behind a south-facing glass façade. The outward-facing surface of the masonry wall is usually painted black to maximize its absorption of solar radiation. During the daytime, solar radiation is absorbed by the masonry wall with the result that the air between the wall and the glass warms up. This causes the air to circulate through vents at the top and bottom of the wall and into the room space, thus warming it. At night the vents in the wall are sealed and the wall transfers heat energy by radiation and convection to the room space.

It is possible to increase the amount of solar radiation collected by a Trombe wall by placing a reflective surface directly on the ground in front of the façade. This material reflects solar radiation onto the thermal storage wall and thus increases its effectiveness.

Trombe walls work best in cold, clear climates which experience large amounts of solar radiation, such as those found at altitude in southern Europe. They are much less effective in northern European climates where cloud cover is often extensive in winter.

Another *indirect gain* technique, which has been used in the USA, is the solar roof pond. As well as providing passive heating in winter this system can also provide cooling in

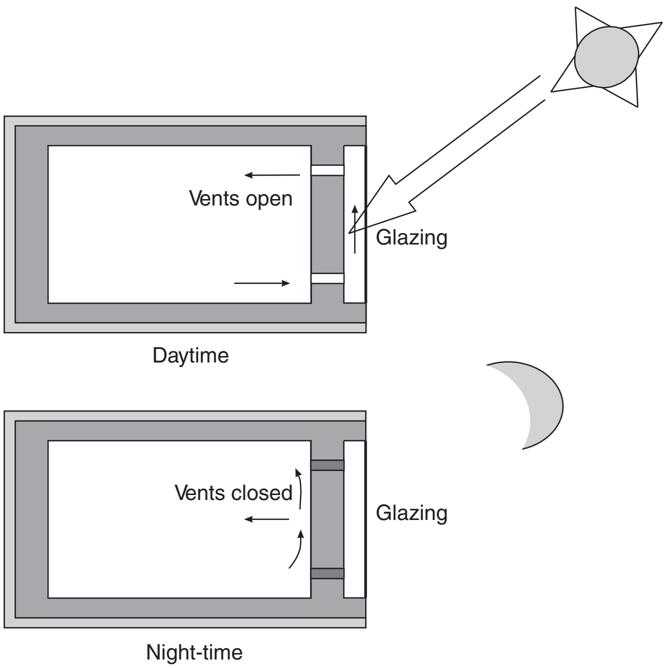

FIG 15.4 Trombe wall operation.

summer. It involves constructing a pond on a flat roof. In winter during the daytime the pond absorbs solar energy. At night the warm pond conducts heat through the roof structure and warms the rooms below by radiation. It is necessary at night in winter to cover the pond with movable insulation material. In summer, the pond can be used to provide passive cooling. Overnight the pond is cooled by exposing it to the night air and once cooled, the water mass is used to draw heat from the space below.

15.2.3 Isolated Gain Techniques

Isolated gain solar heating is essentially a hybrid of the direct and indirect gain systems and involves the construction of a separate sun room adjacent to a main living space. In the *isolated gain* system, solar radiation entering the sun room is retained in the thermal mass of the floor and the partition wall. Heat from the sun room then passes to the living space by conduction through the shared wall at the rear of the sun room and by convection through vents or doors in the shared wall. One classic example of an *isolated gain* system is the use of a south-facing glass conservatory on the side of a house. A typical isolated gain system is shown in Figure 15.5.

15.2.4 Thermosiphon Systems

If a flat solar collector containing water or air is placed below a heat exchanger, a thermosiphon will be created. As the fluid heats up in the solar collector it becomes less

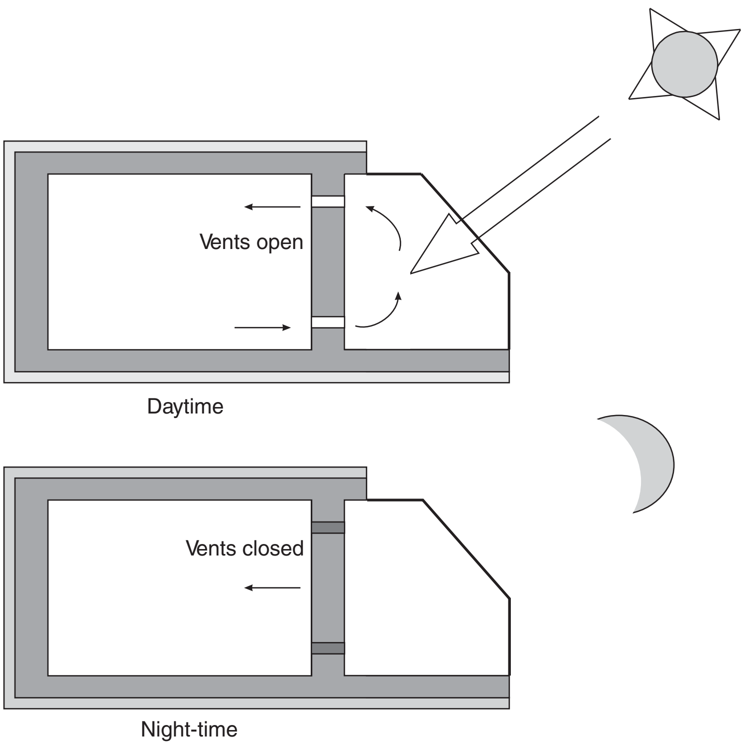

FIG 15.5 Operation of an isolated gain system.

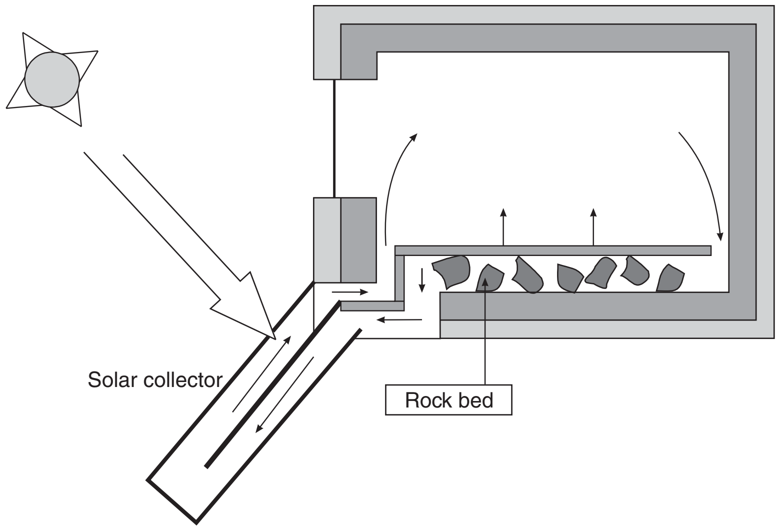

FIG 15.6 A thermosiphon system.

dense and more buoyant and thus rises to the heat exchanger. As the hot fluid travels through the heat exchanger it cools down and so drops to the solar collector below, where the whole process starts over again. It is possible to heat buildings passively by the use of a solar thermosiphon. In such a system the south-facing solar collectors are placed at a level lower than the room space. Warm air from the collectors is allowed to circulate around a floor void filled with rocks. During the daytime the hot air produced by the solar collectors is used to heat up the rocks and during the night-time the rocks give up their heat by convection to the room space (as shown in Figure 15.6).

15.3 Passive Solar Cooling

The term *passive solar cooling* is a very loose one, which can be used collectively to describe a variety of passive cooling techniques, some of which directly utilize solar energy. However, it is true to say that passive solar cooling has more to do with defending buildings against solar energy than utilizing it. Many buildings, especially large commercial buildings, experience overheating problems during the summer months. These problems often arise because of poor building envelope design. Rather than defending against solar gains, many buildings possess envelopes which actively promote the greenhouse effect, necessitating the installation of large air-conditioning systems. There are instead a wide variety of passive techniques which can be employed to prevent overheating, such as the use of solar shading and stack ventilation. However, in many buildings the use of these techniques alone is not enough to maintain a comfortable environment and so it is necessary to employ supplementary mechanical plant, to provide a mixed-mode solution. For example, while a naturally ventilated building may generally experience low levels of heat gain, in specific areas the heat gains may be high and so air conditioning may be required. It is therefore not uncommon to find 'low energy' buildings which exhibit both *passive* and *mechanical* characteristics.

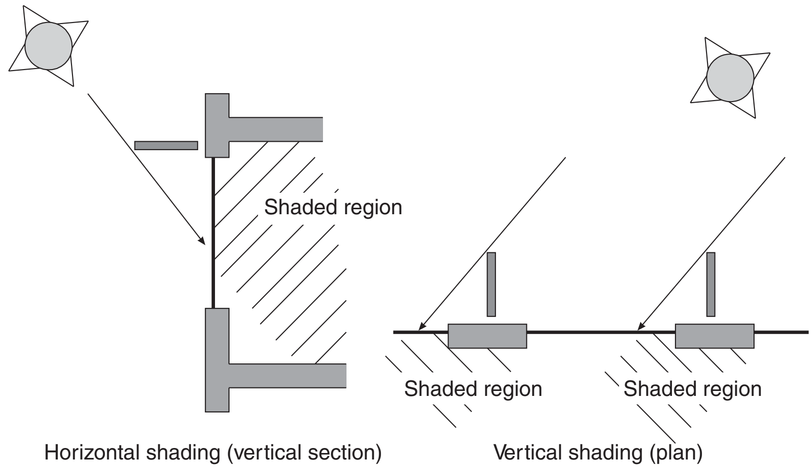

FIG 15.7 External horizontal and vertical shading.

15.3.1 Shading Techniques

By far the best way of preventing overheating during the summer months, or indeed in any part of the year, is to employ adequate solar shading. It is far better to prevent solar radiation from entering a building than trying to deal with it once it has penetrated the building envelope. Shading techniques can broadly be classified as external, internal or mid-pane. External and, to a lesser extent, mid-pane shading techniques offer the best protection since they both prevent solar radiation from penetrating the building envelope. The use of internal shading measures, such as blinds, is much less effective, since although the blinds intercept the incoming solar radiation, they heat up and, in time, convect and radiate heat to the room space.

External shading can be extremely effective at preventing solar heat gains. By using external shades, such as fins, sails, balconies or even structural members, it is possible to achieve both a 'horizontal' and a 'vertical' shading effect (as shown in Figure 15.7). Vertical shading members, in particular, can be very useful since the sun moves through the sky in an arc from east to west and therefore for most of the time is not directly in front of any one window. However, external shading does have its downside. External shades and fins are exposed to the elements and therefore can deteriorate rapidly if not properly maintained. In addition, in city centre locations they can become colonized by pigeons.

Internal shading usually takes the form of horizontal, vertical or screen blinds which the building occupants can control. Although they are good at reducing instantaneous solar gains, they tend to warm up and emit heat into the room space. A compromise between external and internal shading is the use of blinds located in the air gap between the two panes of a double window (as shown in Figure 15.8). As the blinds warm up, heat is trapped in the window cavity and relatively little enters the room space. In some advanced window designs, the warm air produced in this cavity is vented either to outside or to the room space depending on whether additional heating or cooling is required (see Figure 15.8).

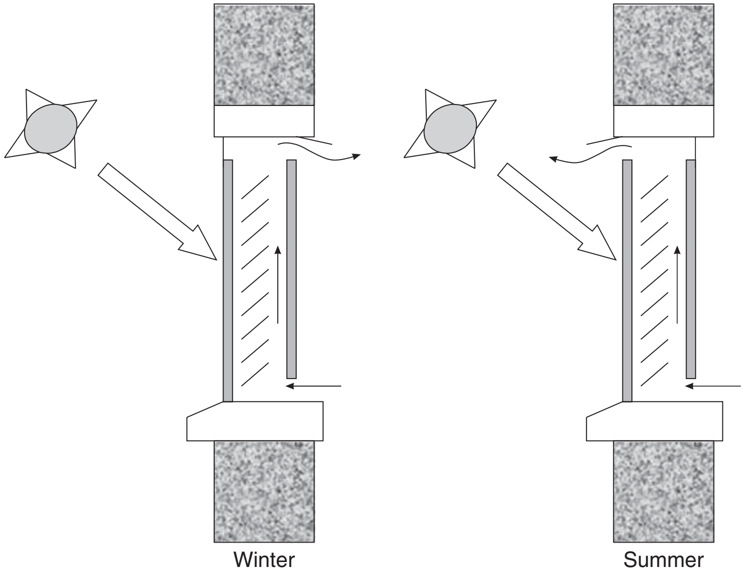

FIG 15.8 Mid-pane shading.

15.3.2 Solar Control Glazing

Figure 15.9 gives a breakdown of the component energy flows to and from a 6 mm clear float glass pane. It can be seen that approximately 78% of the incident solar radiation is transmitted directly through the glass, which explains why sunshine has such an instantaneous effect on the occupants of buildings. Approximately 7% of the incident radiation is reflected and the glass absorbs a further 15%. The heat which is absorbed warms up the glass and after a period of time the warm glass emits heat, both inwards and outwards, by radiation and convection.

It is possible to significantly reduce solar heat gains by using solar control glazing. This can be divided into two broad categories, solar absorbing and solar reflecting glass. Solar absorbing glass is body-tinted, typically bronze, grey, blue or green, using a variety of metal oxides. It works in a similar way to conventional sunglasses by reducing the overall transmission of solar radiation through the window. In doing so it also cuts down the transmission of light through the window. Solar absorbing glass exhibits much higher absorption properties than normal clear glass, with up to 70% absorption being achieved with bronze-tinted glass [7]. However, it should be noted that although much of the incident solar energy is absorbed, it is eventually re-emitted by the glass, with some of the re-emitted heat entering the interior of the building. Solar reflecting glass is, as the name suggests, highly reflective. The high reflection qualities of the glass are achieved by applying a thin layer of metal oxide to the external surface. Solar reflecting glass can be manufactured in a variety of colours, including silver, bronze, blue, green and grey. The mirrored surface of the glass reflects much of the solar radiation which falls on it and is more effective at cutting down the transmission of solar radiation than solar absorbing glass. It is important to note that this type of

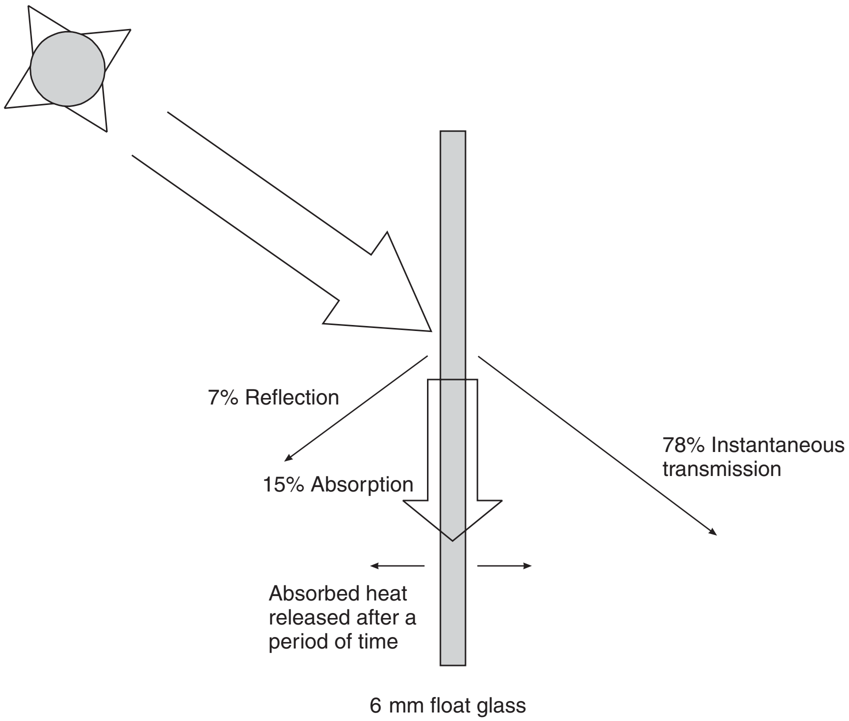

FIG 15.9 Radiation, reflection and absorption for 6 mm clear float glass.

glass reflects large quantities of solar radiation and that this can cause problems in surrounding buildings, which may overheat if care is not taken at the design stage.

15.3.3 Advanced Fenestration

One of the characteristics of many passive/mixed-mode buildings is the use of sophisticated fenestration systems to minimize solar heat gains. Windows in such buildings are often required to perform a number of different and sometimes conflicting tasks, including:

- Enabling daylight to enter the building
- Promoting natural ventilation
- Promoting solar heating
- Reducing solar heat gains
- Preventing the ingress of noise from outside
- Maintaining building security.

These tasks are usually achieved by installing complex window units, which incorporate some or all of the following features:

- Solar control glazing (e.g. solar reflecting or absorbing glass)
- External shading
- Internal or mid-pane blinds
- Openable windows or vents.

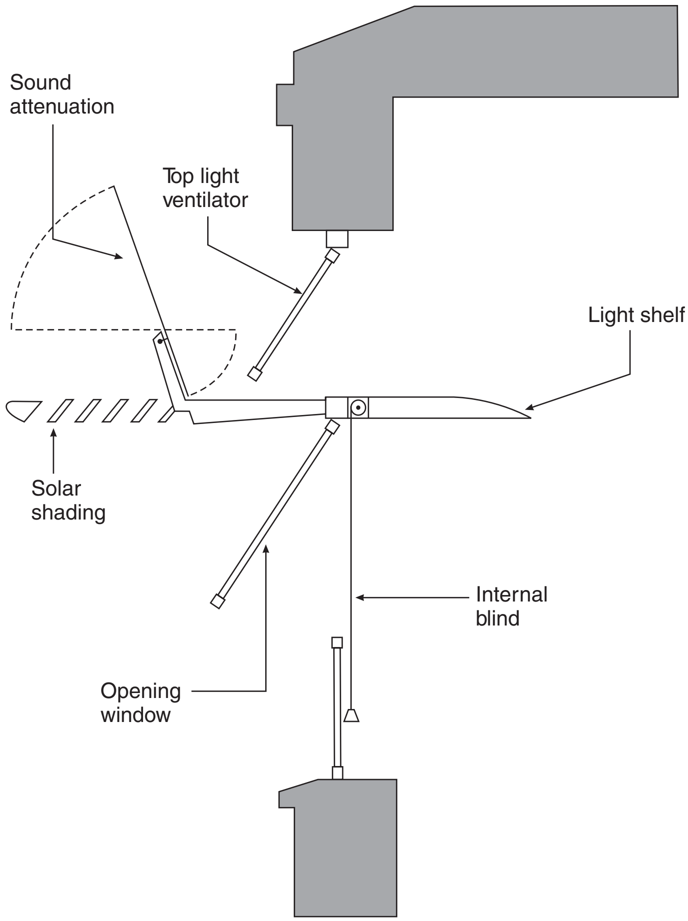

FIG 15.10 Typical advanced fenestration system.

In addition to the above features, many fenestration systems utilize light shelves to maximize daylight and minimize energy consumption on artificial lighting. Figure 15.10 shows a typical advanced fenestration system which might be found in a *passive* or *mixed-mode* building. Such fenestration systems are complex and resemble a 'Swiss army penknife'. It is important to appreciate the crucial role played by such windows. In many advanced naturally ventilated buildings the whole environmental control strategy is dependent on the successful operation of these complex windows. If for any reason they cannot be easily operated, the whole ventilation strategy becomes flawed and the internal environment may become uncomfortable.

15.3.4 Natural Ventilation

One of the key components of any *passive cooling* strategy is the use of natural ventilation, which can be divided into two basic strategies, cross-ventilation and buoyancy-driven (or stack) ventilation. Of the two strategies, stack ventilation is generally

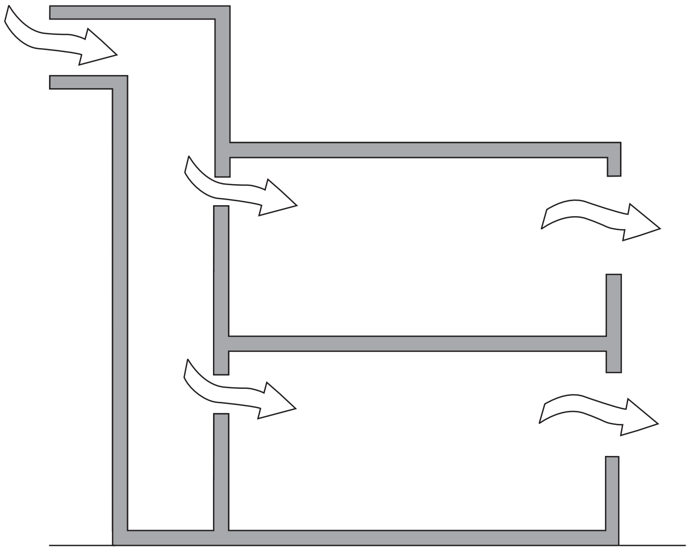

FIG 15.11 The use of a wind-scoop to produce cross-ventilation.

more predictable and more reliable than cross-ventilation. This is because, unlike cross-ventilation, stack ventilation is not dependent on wind speed or wind direction, both of which can be extremely variable. The use of stack ventilation is therefore more commonly found in passively controlled buildings than cross-ventilation.

Cross-ventilation occurs when openings are placed on opposite sides of a building, so that wind pressure pushes air through the room spaces. As air moves through a building it picks up heat and pollutants, and its temperature rises. This limits the width of room space which can effectively be cross-ventilated. It is recommended that plan width of a cross-ventilated space should not exceed five times the floor to ceiling height [10], which usually results in a maximum width of 14 m or 15 m. As a result of this, cross-ventilation tends to be restricted to buildings which have narrow plan widths.

Although cross-ventilation is normally achieved by opening windows, in hot desert countries, wind-scoops are often used (as shown in Figure 15.11). Wind-scoops capture the wind at high level and divert it through the occupied spaces in the building, thus cooling the interior. Wind-scoops can be particularly effective in regions where there is a dominant prevailing wind direction.

Stack ventilation relies on the fact that as air becomes warmer, its density decreases and it becomes more buoyant. As the name suggests, stack ventilation involves the creation of stacks or atria in buildings with vents at high level (as shown in Figure 15.12). As air becomes warmer due to internal and solar heat gains, it becomes more buoyant and thus rises up the stacks where it is exhausted at high level. In doing this a draught is created which draws in fresh air at low level to replace the warm air which has been displaced. Stack ventilation has the beauty of being self-regulating; when building heat gains are at their largest, the ventilation flow rate will be at its largest, due to the large buoyancy forces.

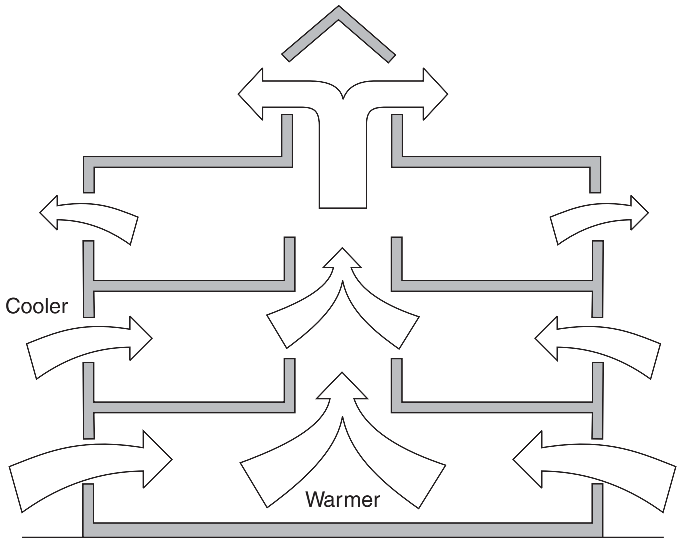

FIG 15.12 Stack ventilation.

The stack effect is driven by the pressure difference between air entering at low level and air leaving at high level. This can be calculated using eqn (15.1):

$$\text{Pressure difference, } \Delta P = gh(\rho_o - \rho_i) \qquad (15.1)$$

where ΔP is the pressure difference between inlet and outlet (Pa), h is the height difference between inlet and outlet (m), ρ_i and ρ_o are the densities of air at inlet and outlet (kg/m^3), and g is the acceleration due to gravity (i.e. 9.81 m/s^2).

The density of air at any temperature can be determined using eqn (15.2):

$$\text{Density of air at temperature } t, \rho_t = 1.191 \times \frac{(273+20)}{(273+t)} \qquad (15.2)$$

where 1.191 kg/m^3 is the density of air at 20°C. It can be seen from eqns (15.1) and (15.2) that the buoyancy force depends on the:

- Height difference between inlet and outlet vents.
- Temperature difference between the internal and external air.

The air volume flow rate drawn by the stack effect can be determined by:

$$V = C_d A_n \sqrt{[(2gh(\rho_o - \rho_t))/\rho_{av}]} \qquad (15.3)$$

where V is the volume flow rate of air (m^3/s), C_d is the coefficient of discharge of openings, A_n is the equivalent area of openings (m^2), and ρ_{av} is the average density of air (kg/m^3). The equivalent area of the openings (A_n) can be determined using eqn (15.4).

$$\frac{1}{(\Sigma A_n)^2} = \frac{1}{(\Sigma A_{in})^2} + \frac{1}{(\Sigma A_{out})^2} \qquad (15.4)$$

where ΣA_{in} is the combined free area of inlet vents (m^2), and ΣA_{out} is the combined free area of outlet vents (m^2).

Example 15.1

A shopping mall is to be cooled using stack ventilation. The mall has vents at low level and in the roof. Given the below data, determine:

(i) The pressure difference driving the stack ventilation.
(ii) The ventilation air flow rate.
(iii) The cooling power produced by the stack ventilation.

Data:

Free area of top vents = 12 m^2
Free area of lower vents = 6 m^2
Height difference between vents = 35 m
Mean internal air temperature = 32°C
External air temperature = 22°C
Coefficient of discharge of openings is 0.61.

Solution

The equivalent area of openings is determined as follows:

$$\frac{1}{(\Sigma A_n)^2} = \frac{1}{6^2} + \frac{1}{12^2}$$

Therefore,

$$\Sigma A_n = 5.367 \text{ m}^2$$

The density of air at 22°C is

$$\rho_{22} = 1.191 \times \frac{(273+20)}{(273+22)} = 1.183 \text{ kg/m}^3$$

The density of air at 32°C is

$$\rho_{32} = 1.191 \times \frac{(273+20)}{(273+32)} = 1.144 \text{ kg/m}^3$$

(i) The pressure difference can be determined by using eqn (15.1):

$$\text{Pressure difference} = 9.81 \times 35 \times (1.183 - 1.144) = 13.4 \text{ Pa}$$

(ii) The volume flow rate can be determined by using eqn (15.3):

$$\text{Volume flow rate} = 0.61 \times 5.367 \times \sqrt{\left[\frac{2 \times 13.4}{0.5 \times (1.183 + 1.144)}\right]} = 15.71 \text{ m}^3/\text{s}$$

FIG 15.13 Queen's Building at De Montfort University, Leicester.

(iii) Cooling power $= \dot{m}C_p(t_i - t_o)$

where $\dot{m}$ is the mass flow rate of air (kg/s), C_p is the specific heat capacity of air (i.e. 1.025 kJ/kg K), and t_i and t_o are the internal and external air temperatures (°C).

Therefore,

$$\text{Cooling power} = 15.71 \times [0.5 \times (1.183 + 1.144)] \times 1.025 \times (32 - 22) = 187.36 \text{ kW}$$

When employing stack ventilation it is important to remember that the stack effect diminishes the further up the building one goes, because the height difference reduces. The air inlet sizes must therefore increase as one travels up a building in order to maintain the same volume flow rate at each floor level. Because the stack effect diminishes towards the top of a building, it is often worth considering an alternative method of ventilation on upper floors.

15.3.5 Thermal Mass

During the 1990s in Europe and the UK a new generation of low energy buildings was constructed, which made extensive use of thermally massive surfaces. Two of the finest examples of these buildings are the Queen's Building at De Montfort University, Leicester [8,9] (see Figure 15.13) and the Elizabeth Fry Building at the University of East Anglia [10] (see Figure 15.14). These buildings use thermal mass as an integral part of their environmental control strategy to produce a thermally stable internal environment.

Thermal mass can be utilized in buildings to perform three separate, but interrelated, roles:

- Mass can be added to the building envelope to create thermal inertia, which damps down the extremes of the external environment.

FIG 15.14 Elizabeth Fry Building at the University of East Anglia.

- Exposed mass can be added internally to create a high-admittance environment which is thermally stable.
- Mass can be added either separately or to the building structure to create a thermal store which can be used to cool buildings.

One unique feature of many 'high mass/low energy' buildings is their use of exposed mass to create a high-admittance internal environment. In most buildings the widespread use of suspended ceilings and carpets effectively converts otherwise thermally heavyweight structures into thermally lightweight ones, creating a low-admittance environment which is poor at absorbing heat energy. Surface temperatures tend to rise in such buildings, making it necessary to get rid of heat gains as they occur. This is one of the main reasons why air conditioning has become a requirement in so many office buildings. However, by exposing the mass of the building structure it is possible to form a high-admittance environment, which can successfully be utilized to combat overheating.

The creation of a high-admittance environment has implications on the comfort of occupants. It can be seen from the discussion in Sections 10.2 and 13.7 that it is the *dry resultant temperature* and not the air temperature which is critical to human comfort. Provided that room air velocities are less than 0.1 m/s, dry resultant temperature can be expressed as:

$$\text{Dry resultant temperature } t_{res} = 0.5t_a + 0.5t_r \qquad (15.5)$$

where t_r is the mean radiant temperature (°C), and t_a is the air temperature (°C).

By exposing the mass of the building structure it is possible to create a high-admittance environment and thus reduce the *mean radiant temperature* and the dry resultant temperature of the internal space. Given that the dry resultant temperature is the average of the sum of the air temperature and the mean radiant temperature, it is possible to allow the internal air temperature to rise in summer without any noticeable discomfort to the occupants, provided that the mean radiant temperature is maintained at a lower temperature than would be the case in a conventional building with suspended ceilings.

In terms of thermal storage capacity, floors are by far the single most important element within any building. A 50 mm deep 'skin' of exposed concrete can store in the region of 32 $Wh/m^2\,°C$, giving it considerable potential to provide cooling, if utilized correctly.

Buildings with a high mass envelope are extremely good at reducing peak solar heat gains, because the mass increases the thermal inertia of the building. With heavy masonry walls the time lag between the incident solar radiation occurring on the external face and the heat being conducted to the interior is often in excess of 12 hours. The overall effect is therefore to dampen down the internal diurnal temperature range, thus minimizing peak heat gains. This results in a reduction in the required capacity of any air-conditioning plant which may have to be installed.

15.3.6 Night Venting

While the use of exposed concrete floor soffits may result in a high-admittance environment, problems can still arise if the structure is not periodically purged of heat. This is because the mean radiant temperature will steadily rise as the floors absorb more and more heat, until conditions become unacceptable. One effective low cost method by which heat can be purged from a building structure is by night venting. In terms of heat removal capability, ventilation is at its least effective during the daytime, when the difference in temperature between the interior of a building and the external ambient is small. In heavyweight buildings, night ventilation is much more beneficial, since the temperature differentials are much greater than during the daytime.

Therefore, with night venting it is possible to make the building structure cool, enabling the occupants and equipment to radiate heat to the exposed soffits of the floor slabs.

Night venting involves passing cool outside air over or under the exposed concrete floor slabs so that good heat transfer occurs. This can be done either by natural or by mechanical means. At its most rudimentary night venting may simply entail the opening of windows at night (see Figure 15.15), while a more sophisticated approach may involve a dedicated mechanical night ventilation system and the use of floor voids (see Figure 15.16). If floor voids are used in conjunction with a night venting scheme, then the cool slab can be used to pre-cool the supply air prior to its introduction to the room spaces. In addition, the use of a floor void allows displacement ventilation to be utilized.

15.3.7 Termodeck

When creating a night venting scheme it is important to ensure good thermal coupling between the air and the mass of the concrete floor, and also that fan powers are kept to a minimum. One system which achieves this objective well is the Swedish Termodeck hollow concrete floor slab system.

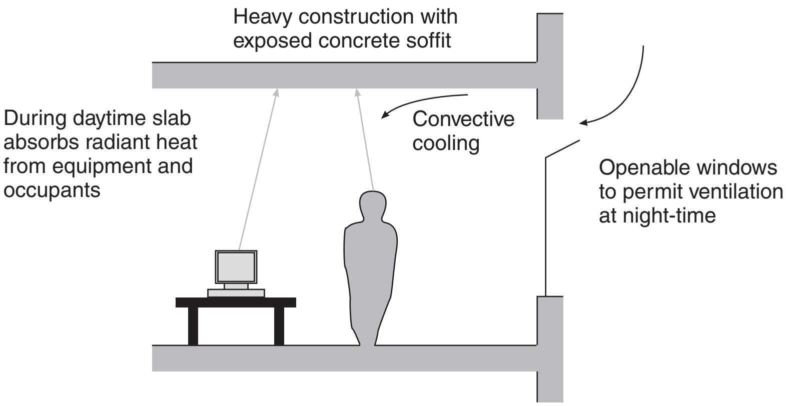

FIG 15.15 Simple night venting scheme in which the windows are opened during the night.

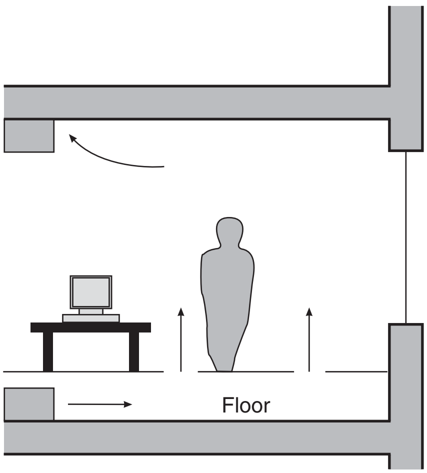

FIG 15.16 Night venting scheme where the ventilation air is introduced through floor void.

The Termodeck system has been used successfully in many locations throughout northern Europe and in the UK, notably in the Elizabeth Fry Building [10] and the Kimberlin Library Building at De Montfort University [11]. The Termodeck system ensures good thermal coupling between the air and the building mass by pushing ventilation air through the hollow cores in proprietary concrete floor slabs (as shown in Figure 15.17). By forming perpendicular coupling airways between the hollow cores, it is possible to form a 3 or 5 pass circuit through which supply air may pass, thus ensuring good heat transfer. During periods in which cooling is required, outside air at ambient temperature is blown through the hollow core slabs for almost 24 hours of the day. Overnight, the slab is cooled to approximately 18–20°C, so that during the daytime the incoming fresh air is pre-cooled by the slab before entering the room space. By exposing the soffit of the slab it is also possible to absorb heat radiated from occupants and equipment within the space.

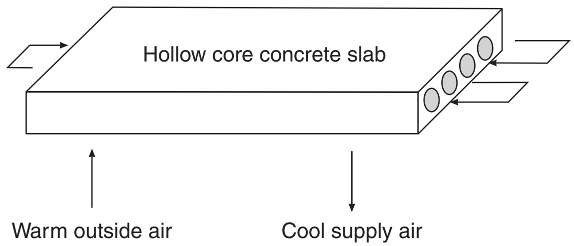

FIG 15.17 The Termodeck system.

The Termodeck system is particularly worthy of note because it produces buildings which are extremely thermally stable and comfortable without the need for any refrigeration. The example of the Elizabeth Fry Building illustrates this fact very well. In a study of low energy buildings in the UK [12], the performance of the Elizabeth Fry Building was outstanding. This building achieved the highest comfort score, while at the same time being one of the lowest consumers of energy; its electrical energy consumption in 1997 was only 61 kWh/m^2 and the normalized gas consumption for that year was 37 kWh/m^2 [10], which compares very favourably with the corresponding values of 128 kWh/m^2 and 97 kWh/m^2 set out in *Energy Consumption Guide 19* for good practice air-conditioned office buildings in the UK [13].

15.4 Building Form

The decision to utilize a passive environmental control strategy can put severe constraints on overall building form. For example, if natural ventilation is used to promote air movement, it will inevitably lead to the creation of a narrow plan building, unless atria or central ventilation stacks are used. This is because passive buildings are supposed to be climate responsive. Therefore the further an internal space is from an external surface, the less chance there is of harnessing the natural resources of the external environment. The use of a passive solar heating strategy also results in a narrow plan building, but with large areas of south-facing glazing. For this reason, passive solar heating schemes tend to be restricted to small- and medium-sized buildings. It is very difficult to use passive solar heating effectively on large deep plan buildings, not least because such buildings tend to overheat for large parts of the year and thus primarily need to be defended against solar heat gains.

Because larger commercial and public buildings generally experience overheating problems, when a passive strategy is applied to the design of these buildings it is usually a cooling/natural ventilation strategy rather than a solar heating one. This means that these so-called *advanced naturally ventilated* buildings all tend to utilize the same generic design strategies and technologies. Broadly speaking, these generic technologies/strategies are as follows:

- The use of a heavily insulated outer envelope.
- The use of carefully designed and often complex fenestration, which minimizes solar gains and building heat losses, whilst maximizing daylight penetration. It is also a requirement that the windows can be opened.

- The use of stacks or atria to promote stack ventilation.
- The use of night ventilation to purge the building structure of the heat accumulated during the daytime.
- The careful use of exposed building mass to dampen down swings in internal space temperature, and to promote radiant and convective cooling.

One of the characteristics of these advanced naturally ventilated buildings is that they often have complex façades with openable windows, vents, blinds, external shades and even light shelves. These façades incorporate advanced fenestration systems which have many moving parts and which are often controlled by a building management system (BMS). Such complex façades are necessary because the absence of internal mechanical services forces the external skin of the building to become the primary climate modifier and to perform a wide variety of tasks (e.g. daylighting, defending against solar radiation, ventilation and preventing the ingress of external noise). By creating a complex skin, the designers of such buildings are effectively distributing 'complexity' all around the building rather than concentrating it in a central plant room. This degree of complexity in the skin can have a considerable impact on both the performance of the occupants and the facilities management regime which must be adopted.

In contrast to advanced naturally ventilated buildings, the use of a mechanical ventilation system offers considerably more flexibility and enables deeper plans to be utilized. In this respect, the Termodeck system appears to offer great potential, as it facilitates good thermal coupling between the air and the building mass without the need for a particularly complex façade or an open plan interior.

The use of the generic passive technologies/strategies described above puts constraints on building design and dictates the building form. With larger buildings the use of natural ventilation often results in buildings which have atria. These buildings comprise a narrow rectangular plan wrapped around an atrium, which gives the appearance of a deep plan building. Vents in the top of the atrium are used to promote buoyancy-driven ventilation and air is drawn through vents or windows in the façade. As a result, passively cooled and ventilated buildings tend to look similar to each other, characterized by the use of atria or stacks and complex façade. Figures 15.18–15.21 show sections through four recently constructed passively cooled buildings in the UK: the Learning Resource Centre at Anglia Polytechnic University, Chelmsford; the Ionica Headquarters, Cambridge; the Inland Revenue Headquarters, Nottingham; and the School of Engineering, De Montfort University, Leicester.

It can be seen from the illustrations above that all four buildings exhibit many similarities. In the Anglia Polytechnic and Ionica buildings the designers have used atria to produce buoyancy-driven ventilation, whereas in the other two buildings purposely built stacks have been employed. Table 15.1 summarizes the features of all four buildings.

It should be noted that although some of the above buildings, especially the De Montfort building, do not appear to be narrow plan, from a ventilation point of view they are all narrow plan buildings. The practical maximum width of space which can be naturally ventilated is approximately 15 m. This dimension limits the form of the building to a narrow plan format. Nevertheless, by constructing a narrow plan rectangular

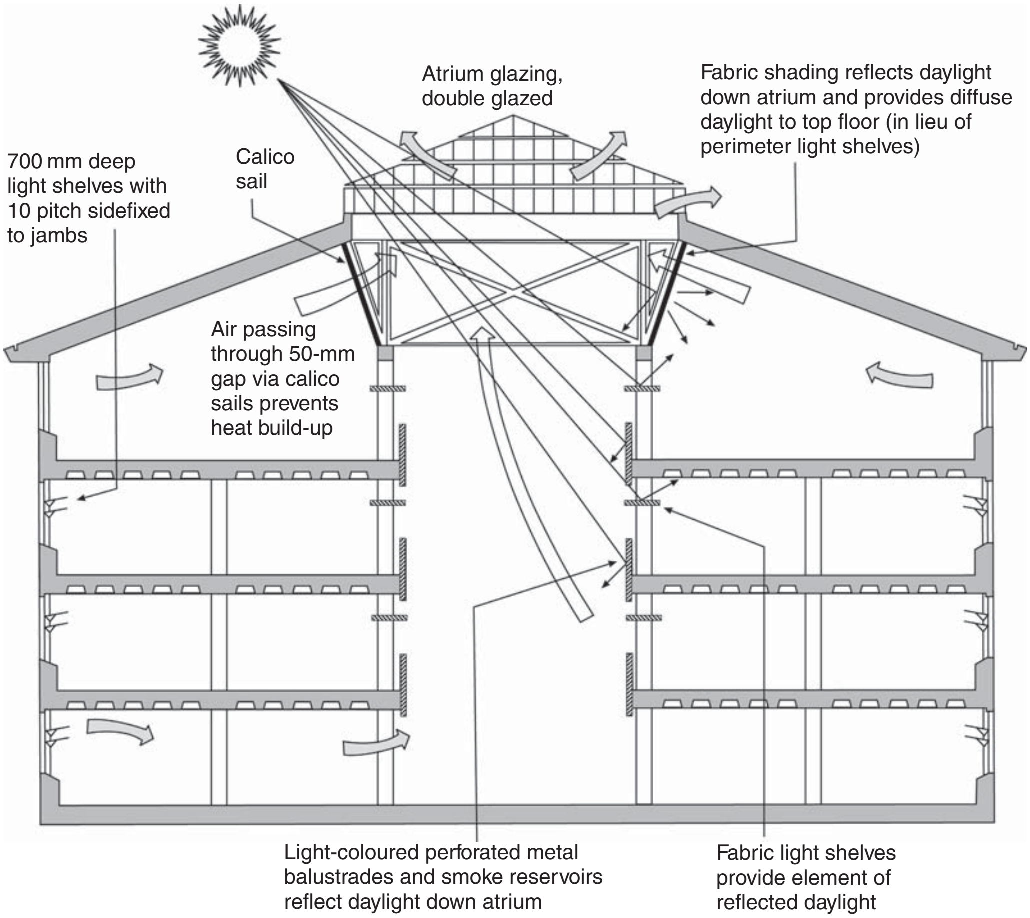

FIG 15.18 Learning Resource Centre at Anglia Polytechnic University, Chelmsford [8].

building around an atrium, which is essentially a glass-covered courtyard, it is possible to achieve the appearance of a deep plan building. In the case of the De Montfort building, the deeper plan is achieved by putting ventilation stacks in the middle of the building.

15.5 Building Operation

The use of a passive environmental control strategy not only affects overall building form, it can also have a considerable impact on the operation of buildings and the performance of their occupants, especially if the building is large and naturally ventilated. By relying on a sophisticated envelope as the primary climate modifier and taking a minimalist approach to the mechanical building services, designers of such buildings need to be careful that they do not create an environment which hinders the performance of the occupants. Although designers may feel that they have produced a comfortable low energy building, the reality may be that it is detracting from the occupier's core business, rather than adding to it. With this in mind, it should be remembered that

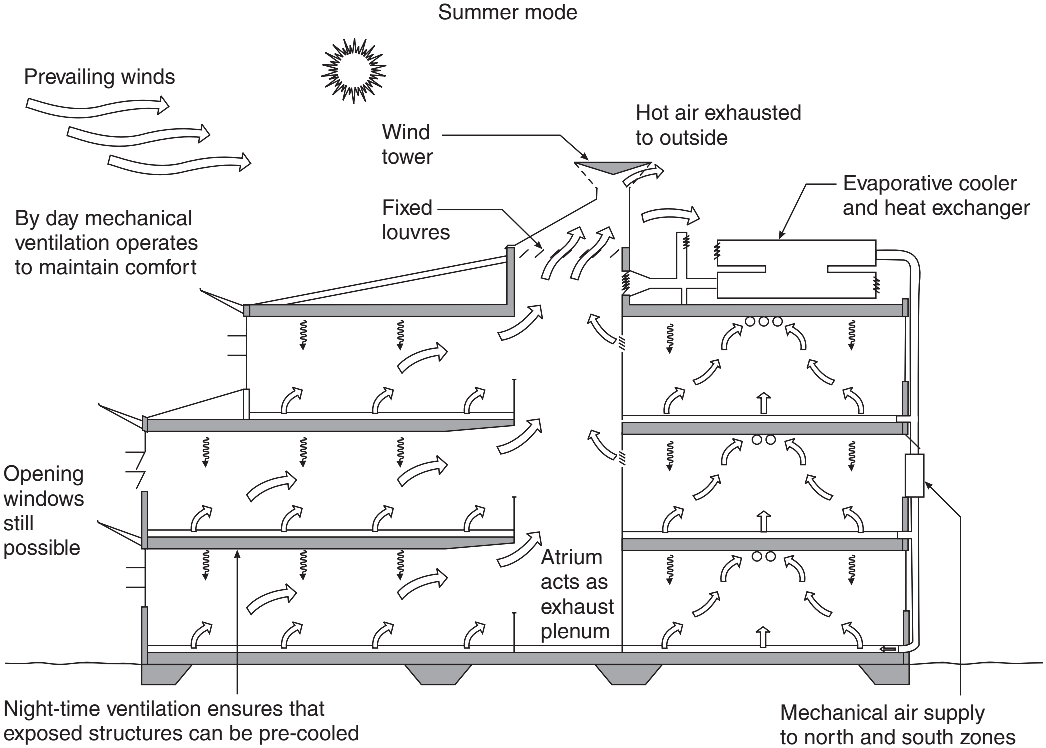

FIG 15.19 Ionica Headquarters, Cambridge [8].

any property which gets a reputation for being uncomfortable, or unfit for its purpose, is unlikely to gain in value [14].

A study of prominent low energy buildings in the UK [12] found that higher levels of occupant satisfaction were easier to achieve in buildings which exhibited:

- A narrow plan form.
- Cellularization of working spaces.
- A high thermal mass.
- Stable and thermally comfortable conditions.
- Control of air infiltration.
- Openable windows close to users.
- A view out.
- Effective and clear controls.

Conversely, occupant satisfaction was harder to achieve in buildings which exhibited:

- A deep plan form.
- Open work areas.
- The presence of complex and unfamiliar technology.
- Situations where occupants had little control over their environment.
- High and intrusive noise levels.

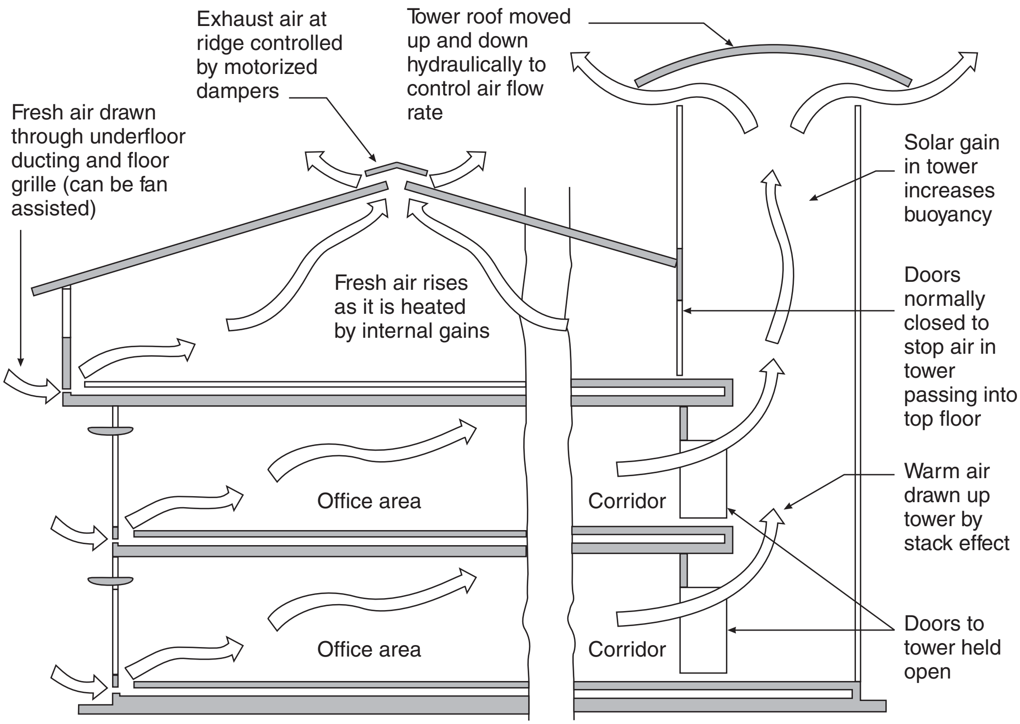

FIG 15.20 Inland Revenue Headquarters, Nottingham [8].

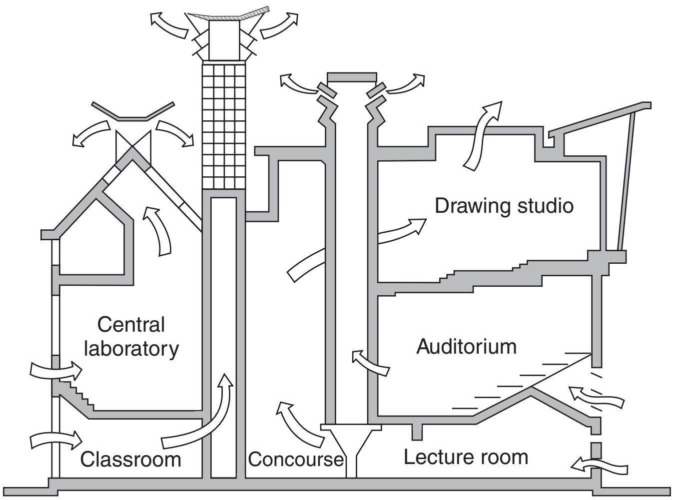

FIG 15.21 School of Engineering (Queen's Building), De Montfort University, Leicester [8].

Inspection of the above lists reveals a fairly consistent picture; in short, people prefer to work close to a window, which they can open, in a quiet cellular office space, which is thermally stable and comfortable. When these criteria are viewed in the context of passive buildings, a mixed picture emerges. Clearly, in some respects *passive* buildings are

TABLE 15.1 Summary of characteristics of sample buildings [8]

Building	Atrium or stacks	Complex windows with shading	Night venting	Exposed high mass soffits	Light shelves	Energy consumed per year (KWh/m^2/year)
Anglia Polytechnic University	Atrium	Yes	Yes	Yes	Yes	82
Ionica Headquarters	Atrium	Yes	Yes	Yes	No	64
Inland Revenue Headquarters	Stacks	Yes	Yes	Yes	Yes	89
De Montfort University	Stacks	No	Yes	Yes	Yes	120

very positive since they tend to provide a high-admittance environment which is thermally stable and comfortable. In other respects they are not so beneficial. Many larger advanced naturally ventilated buildings have large open plan internal spaces because central atria or vent stacks are used. In these buildings many occupants are inevitably located some distance from the windows and therefore have little control over their environment. In addition, the use of large spaces and acoustically hard surfaces can lead to noise problems. Indeed, noise problems have been highlighted as a particular difficulty in advanced naturally ventilated buildings [12]. Given this, and the other reasons mentioned above, it is not surprising that some advanced naturally ventilated buildings display low levels of occupant comfort and productivity [12,15].

The complex nature of the fenestration required in advanced naturally ventilated buildings can be the cause of numerous problems and is therefore worthy of closer inspection. The issue of who has control over the opening of windows is of particular importance. In large naturally ventilated buildings, particularly those which require night ventilation, the function of the whole environmental control strategy can be impaired if, for any reason, certain windows are not opened. Consequently, BMS are often used to control the operation of windows, as the occupants cannot be relied upon to open the windows when required. This automatically brings the user into conflict with the BMS system with the result that occupants sitting near windows may be unable to shut the windows when they experience a draught, or conversely, open them when they feel too hot. If a BMS system is not used, issues of conflict can still arise when, for example, the occupants next to the windows may close them in situations where those requiring ventilation in the centre of the building need them to be open. The use of complex fenestration systems, with many moving parts, can also result in poor window sealing over a period of time, resulting in unwanted air infiltration.

From a maintenance point of view, complex fenestration can cause problems. The use of external shading and the numerous protruding and moving parts in these fenestration systems means that they are prone to mechanical damage and are difficult to clean. The manufacturers of these systems go to considerable effort to reduce potential cleaning difficulties, but it still remains true that from a facilities management point of view these systems need considerably more attention than conventional windows. A study by Kendrick and Martin has shown that the windows most suited for night venting and BMS system control (i.e. high level top hung and hopper windows) are the most difficult to clean from inside [16]. These advanced fenestration systems have important implications on the flexibility and day-to-day operation of the office space. They are required to be opened by the occupants and are designed to be cleaned from inside. Any desks, bookcases or benches against the external wall inhibit both the ability of the occupants to regulate their environment by opening windows, and the ability to clean and maintain the windows. Consequently, some facilities managers faced with this problem have opted for a 'furniture-free' zone next to the windows, or else have installed movable furniture next to the windows. While making the cleaning of windows easy, such a policy can hardly be considered to be designed to increase the comfort and productivity of building occupants. In addition, forcing the occupants away from the windows means that the potential daylighting zone is reduced and thus more people have to rely on artificial lighting, which in energy efficiency terms is very counterproductive.

Both developers and building tenants desire buildings which contain flexible space capable of being adapted to meet the evolving needs of organizations. This need for flexibility/adaptability has traditionally been resolved by designing deep open plan buildings. From a facilities management viewpoint the use of an advanced natural ventilation strategy imposes severe constraints on the flexibility of the working space. In particular, it is extremely difficult to partition off internal spaces in such buildings because:

- The insertion of full-height partitions may restrict or prevent air movement through the space, thus nullifying its environmental performance.
- It may be difficult to create an acceptable environment within any partitioned office spaces that are created. In a conventional office space it is possible to 'tap' into the nearest mechanical ventilation duct in the ceiling to serve a new space. In a naturally ventilated high mass building there may well be no ceiling and no mechanical ventilation services in the floor. This makes it difficult to adequately ventilate partitioned spaces.
- The lack of a suspended ceiling can lead to flexibility problems when repositioning luminaires.
- In many advanced high mass buildings the exposed floor soffits are formed by deeply recessed concrete floor beams. The geometry of these floor beams can create problems when erecting partitions.

Even if full-height partitions are not installed, the environmental performance of a naturally ventilated space may still be impaired by the insertion of high screens and furniture, which restrict the air flow and thus create 'dead' spots.

From the discussion above it is tempting to conclude that all *passive* and *mixed-mode* buildings result in operational difficulties. However, this is not the case. The example of the Elizabeth Fry Building, which utilizes the Termodeck system, clearly demonstrates that high mass *mixed-mode* buildings can be very successful. Of all the buildings surveyed in the UK study [12], it was the Elizabeth Fry Building which was outstanding. This building achieved the highest comfort score, while at the same time being one of the lowest consumers of energy. Of particular note is the fact that the building produced an extremely stable thermal environment and comfortable internal temperatures during summer without the need for any refrigeration, clearly demonstrating the success of the fabric thermal storage strategy. The reasons for its success are that the building:

- Is thermally stable and comfortable
- Has cellular work spaces
- Has a relatively narrow plan
- Is well sealed and has tight control over air infiltration
- Has windows which can be opened by the occupants.

These are all qualities which tend to promote user comfort and enhance productivity. When the Elizabeth Fry Building is compared with less successful advanced naturally ventilated buildings, it can be seen that its success lies in the fact that the Termodeck system is much more unobtrusive and flexible than the more rigid requirements of the naturally ventilated buildings. For example, the use of mechanical ventilation and hollow core slabs means that the façade of the building can be relatively simple, which frees up the windows so that they can be opened at will by the occupants without impairing the thermal performance of the building. The use of a mechanical ventilation system allows the internal space to be sub-divided into cellular rooms, something which is difficult to achieve in advanced naturally ventilated buildings. It also allows flexibility in the shape and form of the building. Unlike the advanced naturally ventilated buildings where 'complexity' is distributed around the skin of a building, the Termodeck system concentrates 'complexity' in a central plant room where it can easily be controlled and maintained.

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