7. PASSIVE CLIMATE CONTROL FOR CULTURAL INSTITUTIONS

7.1. Passive building strategies

7.1.1. The building as an environmental modifier

All buildings act to modify the ambient climate. A well designed building will not only shelter its contents from the worst of the weather such as rain, wind, and hot sun but also significantly reduce the impact of extremes of temperature and humidity. A building designed specifically for passive environmental control will go further than this. By appropriate planning, choice of materials, and especially the management of ventilation, one can achieve free heating in cool climates and even free cooling in over heated climates.

A poorly designed building on the other hand, will amplify some of the climatic variables. A typical example would be some buildings in the tropics, which all too often, are hotter inside than the maximum temperatures attained outside.

In order to understand the way in which a successful building modifies its interior climate, it is useful to distinguish a number of separate mechanisms.

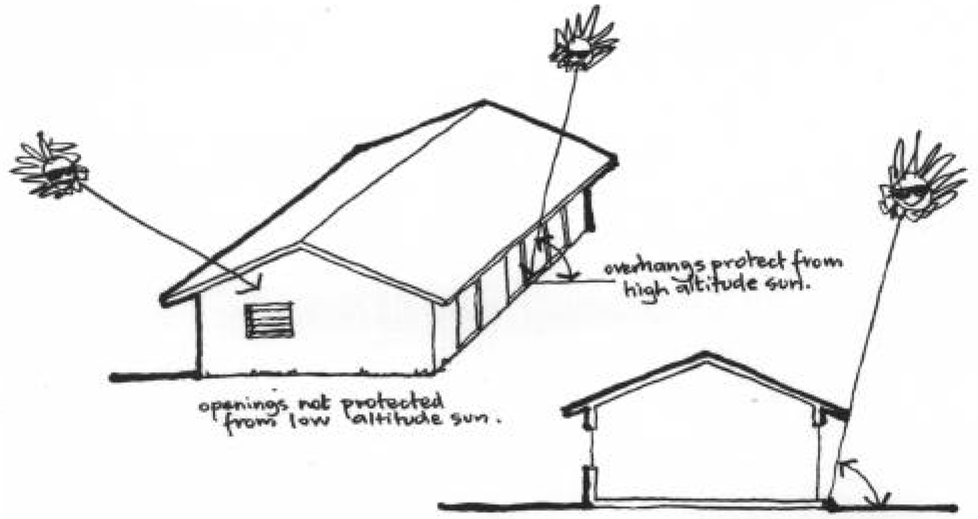
7.1.1.1. Load reduction

The first task of the building fabric is to reduce the impact of ‘climatic loads’ on the building. In hot climates, these loads are primarily solar radiation and elevated daytime temperatures. In cold climates, they are potential heat losses due to cold air temperatures, aggravated by exposure to cold winds.

In hotter climates the interior of a building would normally heat up more than the surrounding external spaces. This happens because, in addition to responding to ambient air temperatures, the building is also subject to solar radiation. While the building fabric is generally efficient at absorbing such radiation through roof, walls, and especially windows, it is far less efficient at re-radiating heat to its surroundings. As a consequence, building interiors often heat up to temperatures far higher than ambient outside at the same time. In order to avoid this happening, the first step is therefore to reduce the building's exposure to solar radiation.

The first step in reducing unwanted solar gain is to make appropriate choices of building orientation. In general, east and west facing facades receive the greatest solar loads in summer, while, in Australia, the north facade actually receives less solar radiation in summer than it does in winter (Fig. 7.1.). A simple rule is, therefore, to reduce the size of east and west facades, and to reduce to a sensible minimum any glazed openings in those facades.

Fig. 7.1. Orientation of building E-W to provide shading to openings in the long walls



Additional protection is achieved primarily by shading, reducing the solar load actually reaching the building fabric. Again, in Australia, north facades are easiest to shade, because a simple overhang will deal precisely with any chosen shading period. Employing reflective building surfaces further reduces the radiation absorbed buildings in warm climates should therefore be generally light in colour. In addition, ventilation is often employed to remove excess heat build-up in the interiors.

It should be stressed that simple load reduction only serves to achieve an interior climate in a building, which is perhaps no worse than the ambient climate. This is particularly true in warm humid climates, where buildings with copious cross ventilation could be said to be no more comfortable than sitting under a shady tree outside.

In cold climates, load reduction is limited to reducing the exposure of the building to such influences as prevailing cold winds. This is achieved by appropriate siting, shelter planting, and a compact building volume with a minimum surface to volume ratio.

7.1.1.2. Insulation

The ability of the building to transmit heat in response to external loads may be modified. This is achieved by increasing the resistance of the building fabric to heat flow; in practical terms by adding insulating materials. This strategy is most beneficial in artificially heated or cooled buildings, because it conserves the energy inputs in the heating or cooling system.

Insulation, especially of roofs, is also a vital part of passive design. However, under some limited circumstances, over-insulation is actually counter-productive. This can occur when shading in hot climates is ineffective, and the insulation actually impedes removal from the building of the excess solar gains.

7.1.1.3. ‘Flywheel’ effects

Appropriately designed buildings will dampen the impact of daily extremes, of both ambient temperature and humidity. Thus, in an over-heated climate, a building interior might be cooler than ambient during the day, and warmer at night. This is achieved mainly by appropriately deploying thermally massive materials, in order to store and release heat. Overall, the building serves to bring interior conditions to a narrower range throughout the day, closer to the average conditions outside. It should be noted that in a cold climate, the same would be true.

Such thermal flywheel effects are generally successful in hot arid climates, where, because of the very large diurnal temperature range, daytime temperatures are too high, and overnight temperatures may well be below comfort levels. When the average temperature for the whole day is in an acceptable range, and if the building achieves a small enough ‘temperature swing’, little other climate modification may be necessary. Clearly, in the under-heated climates, interiors may still end up too cool throughout the 24-hour cycle of the day.

Again, it should be emphasised that dampening thermal fluctuations, while generally beneficial because it achieves more stable environments, achieves no overall cooling in an over-heated climate, nor net heating in an under-heated one.

Humidity variations are also generally smaller inside buildings than outside on the same day. The rate at which interior humidities respond to the ambient is largely determined by the rate and amount of air exchange between the outside and a building interior. In addition, by appropriate choice of materials for their ability to absorb and desorb moisture, a certain degree of humidity buffering can also be achieved (section 9).

7.1.1.4. Selective natural heating or cooling

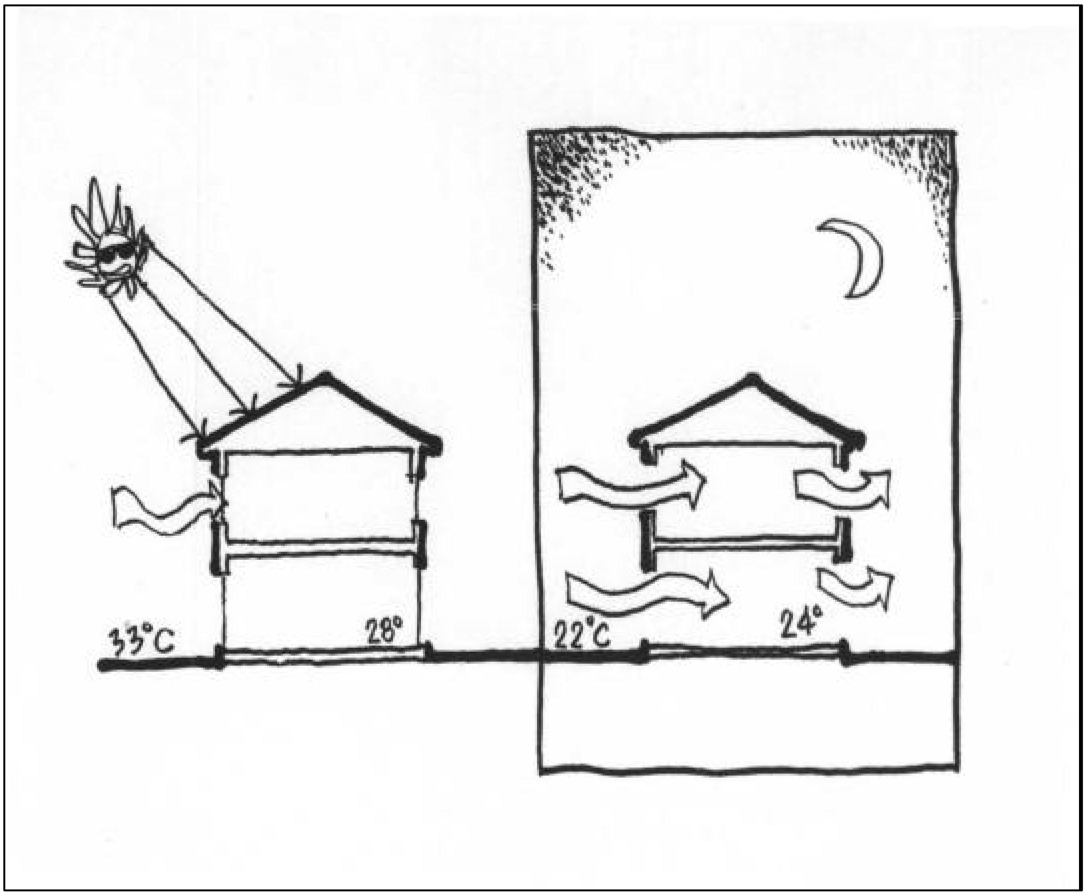
By good design, it is possible to go further than simply reducing extremes, and thereby merely approaching average ambient conditions. To determine whether net heating or cooling is achieved, it is necessary to compare *daily average* temperatures achieved over a period inside, with those outside for the same period.

In an under-heated climate, passive solar design employs orientation for solar gain, insulation to reduce heat losses, and thermal mass for storing admitted heat. By admitting solar gain through glazing, storing it in the ‘over-heated period’ and releasing it at night, it is relatively easy to achieve an interior that is, on average, warmer than the ambient conditions outside. In cool temperate zones, it is theoretically possible to achieve a ‘solar heating fraction’ i.e. the contribution of solar gain to the total heating requirement of a building approaching 100 per cent.

In hot arid climates with large diurnal temperature variations, a combination of shading, thermal mass, and controlled ventilation, can be used similarly to reduce internal temperatures.

Thermal mass in the *exterior* building fabric slows the heat flux such that some of it reverses as the exterior cools, and is given off at the exterior rather than the interior surfaces. *Internal* mass absorbs heat during the overheated period, and is cooled by night ventilation. In a hot arid region, a well designed building with a well managed ‘night flush’ ventilation regime, can expect to reduce daytime maximum temperatures by 40 60 per cent of the diurnal range (Fig. 7.2.).

Fig. 7.2. Night ventilation



Average internal temperatures are more difficult to lower, but monitored results from such buildings in California and Israel have shown a reduction to approximately 1°C below the ambient average. This result should be compared with a ‘closed’ thermally massive building, which would expect to achieve an internal average approximately 3°C above ambient.

In warm humid climates, because of the small diurnal variation in temperature, such net cooling is very difficult, indeed often impossible.

7.1.2. Building elements and systems

Building elements and systems may be classified according to a number of different considerations. Most commonly, we would discuss the building under the headings of floor, walls and roof. Alternatively, it might be useful to distinguish structural elements (those which hold the building up), from cladding (elements which keep the weather out). For the purposes of this discussion, however, building elements will be primarily classified according to functions they perform within a broad environmental control system.

The building as a whole acts as a filter, or modifier of the environment. Under the concept of filter, we can discuss how the various external environmental variables, radiation, convective heat gain/loss, and air exchange are controlled by the external fabric of the building. Under the more general concept of modification, we can discuss the time dependent effects of heat storage and moisture buffering.

Such a conceptual understanding of the role of various components of the building fabric allows an informed discussion of the choice between passive and active environmental controls, and the impact of such choices on other aspects of the building design.

7.1.2.1. Conductive heat loss/gain

Heat flows into and out of buildings through the elements of its external envelope. The main mechanism of heat flow is conduction, the method of transfer of heat where atoms can pass their vibration energy to adjacent atoms in the lattice structure of a solid material. Strictly speaking, conduction can only occur in a homogeneous element, such as a solid brick wall without cavities, whereas practical building materials are made of usually more than one material, have to take up heat from air and give it out to air again, and often have air gaps inside the construction.

So heat loss or heat gain through a building element is determined by the:

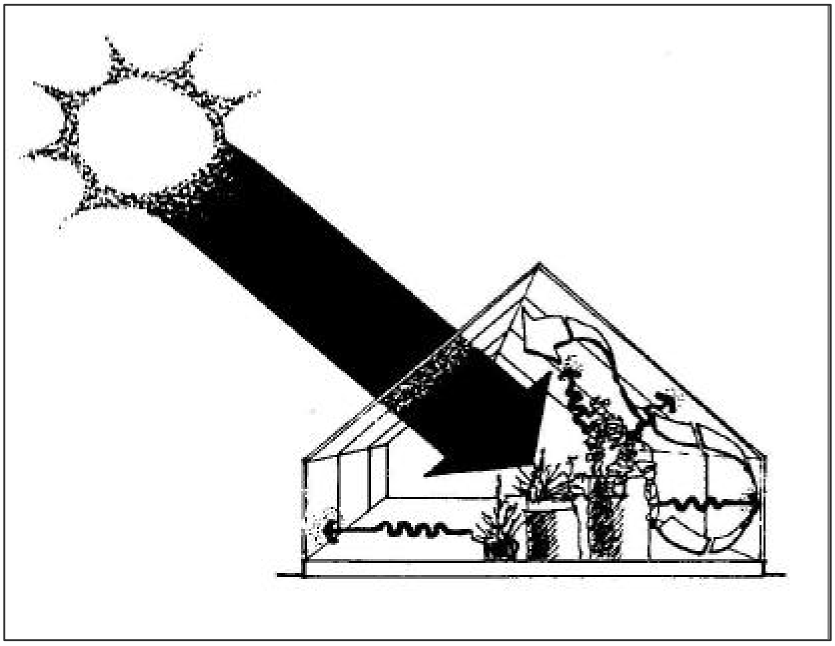
- the area of the element;
- the air speed either side of the element;
- the resistance (R-value) to heat flow of the individual materials;
- the resistance to heat flow of the air spaces (including the ability to transfer heat from a material to the air, then back to another material); and
- the *effective* temperature difference, allowing for radiation effects.

7.1.2.2. Solar radiation and transparent building elements:

Transparent building elements are characterised by the fact that they *transmit* a high proportion of the radiant energy unchanged from one side to the other. The most common transparent building material is glass. Previously, other materials had been used, such as mica, parchment, paper and thin stone panels. These days we also use various plastics, as rigid or flexible sheets.

Conventional soda glass has a particular characteristic that distinguishes it from most other transparent materials. Glass is transparent to all radiation in the solar spectrum, but is substantially opaque to radiation above approximately 3#100 nm (section 3.3). This gives rise to the so-called *glass house effect* (Fig. 7.3.)

Fig. 7.3. Glasshouse effect of glazing



Glasshouse effect. Incoming solar radiation passes through the glass. On striking any surface in the occupied space, the solar radiation is absorbed, thus heating that surface. As the surface (whether it is a wall, floor, furniture, or any other object) heats up, it re-radiates energy, but now at the longer wavelengths. However, the glass is opaque to such longer wavelength radiation, trapping the radiation inside the space. The net effect is that the interior continues to warm up. This is the basis of all passive solar design.

By applying various films to the glass we can balance the transmission characteristics for different parts of the solar spectrum. For instance, an ideal *sun control film* will keep out most of the infra-red, and admit a particular fixed desirable level of the visible spectrum. In contrast a so-called *heat mirror* (the sort of glass ideal for passive solar applications) would admit maximum visible and near infra-red, and be completely opaque and reflective for longer wavelength infra-red radiation. Various additives and films can modify the properties of glazing systems in different ways. Broadly, we have heat absorbing sun control glazing, reflective sun control glazing, and glazing that has its emissivity modified. Increasingly these days, for larger institutions there is merit in considering ‘advanced glazing systems’, which can combine various of these characteristics to achieve heat, light and spectral distribution control characteristics, closely matched to the particular application.

For smaller and passively controlled environments, it is still more fruitful to turn to other, perhaps operable ways of shading the glazing in a building. Obviously, it is better to stop the radiation from reaching the glass in the first place. For this, external devices are the most effective. But internal elements can also work. If we can reflect as much short wavelength radiation as possible as soon as it has entered through the glass, much of it will go straight back out through the glass, and only a small part will be trapped inside. Thus, for instance a dense white roller blind can achieve a shading coefficient of 0.6 even though it is applied at the inside of the glazing.

7.1.2.3. Heat storage and time lag effects

As a material absorbs heat, it warms up. Typically, dense heavy materials are effective at storing heat, while light materials are not so effective.

Periodic Heat Flows. To warm up a particular volume of material, heat must travel inwards from the outer surface of the block, progressively warming up each incremental layer. For the material to give up that heat, the direction of the heat flow must reverse. Heat flows from warmer to cooler material, so this cycle of inwards and outwards flow assumes that the outer layers will vary, from warmer to cooler than the core of the heat storage element.

There are two quite different situations applicable to buildings:

- Heat flows *through* a material typically a solid external wall. The storage of heat in the material causes a *time lag* between initial heating, and the arrival of the peak heat 'wave' at the inside face of the building element.

- Heat flows into, and back to the same face of an element typically the thermal mass stores heat from one part of the day, and gives it up at a later, cooler time of day.

These two cases are fundamentally different. In the first case, a thermally conductive wall of designed thickness (the thickness depending on the delay required) is located on the external walls. The second case is usually an inside element, insulated from the outside, where surface area exposed matters, and only limited thickness is useful.

We would be interested in the first situation, as described previously, in hot climates with large daily variations in ambient temperatures. Roofs and walls can be readily designed to achieve typically five to eight hours ‘lag’ in order to minimise incoming heat loads during a typical day.

Most of the time we are concerned with the second type of heat storage, where heat enters (typically) a concrete slab floor, when there is excess energy coming into the space. The slab is warmed up. Later, when the air temperature is lower than that of the surface of the slab, the heat then flows back out.

This latter type of heat storage is a key component in *passive solar design*, where the excess heat is deliberately admitted into the building, usually by way of appropriately oriented glazing. The excess heat is taken up by the thermal mass, which warns up in the process. As the spaces cool down in the evening and at night, the heat is given up again by the thermal mass, thus limiting the so-called temperature swing of the contained spaces.

As described in the previous section, heat storage capacity in the space is also useful to moderate the effects of unwanted heat transmission from the outside, such as in hot arid climates. The principle of storing heat during the day, and giving a back up at night is identical; but the role of the external fabric changes to keep out heat during the day, and get rid of it at night by ventilation.

7.1.2.4. Ventilation and air exchange:

Air quantity or air velocity? When discussing ventilation, two types must be distinguished. One is the simple supply of 'fresh' air, coupled with the removal of 'stale' air. This type of ventilation is conventionally specified in air changes per unit time. Alternatively, it is prescribed in building codes on the basis of litres/second per occupant. Air change is required in order to achieve a dilution of the build-up of internally generated contaminants, and serves also to remove sensible heat.

Air changes also occur as adventitious infiltration or exfiltration. Even in extremely well detailed buildings, conventional building practices compromise the integrity of the building fabric. Small air paths through the construction are inevitable, most particularly around openings. In fully air-conditioned buildings positive pressurisation will usually assure a small, but steady outward flow of conditioned air.

Additional air exchange occurs as a consequence of the use of the building, through the necessary use of entrances, for both people and goods. In some circumstances, a ‘closed front door’ policy (e.g. using revolving doors at the museum entrance) can limit air exchange with the exterior to a significant degree.

A second type of ventilation is utilised to generate certain surface conditions, such as evaporation from the skin, and is therefore specified in terms of air movement. It may be provided by enhancing natural breezes, or by mechanical means such as fans. In order to be effective, the air stream must pass over the occupant or object. The higher the air velocity, the more effective such ventilation, but a practical limit is imposed by damage or nuisance value. It should be self-evident that any building whose ventilation is strongly linked to the outside will, by definition, be less effective as protection against air pollution than one in which ventilation is controlled.

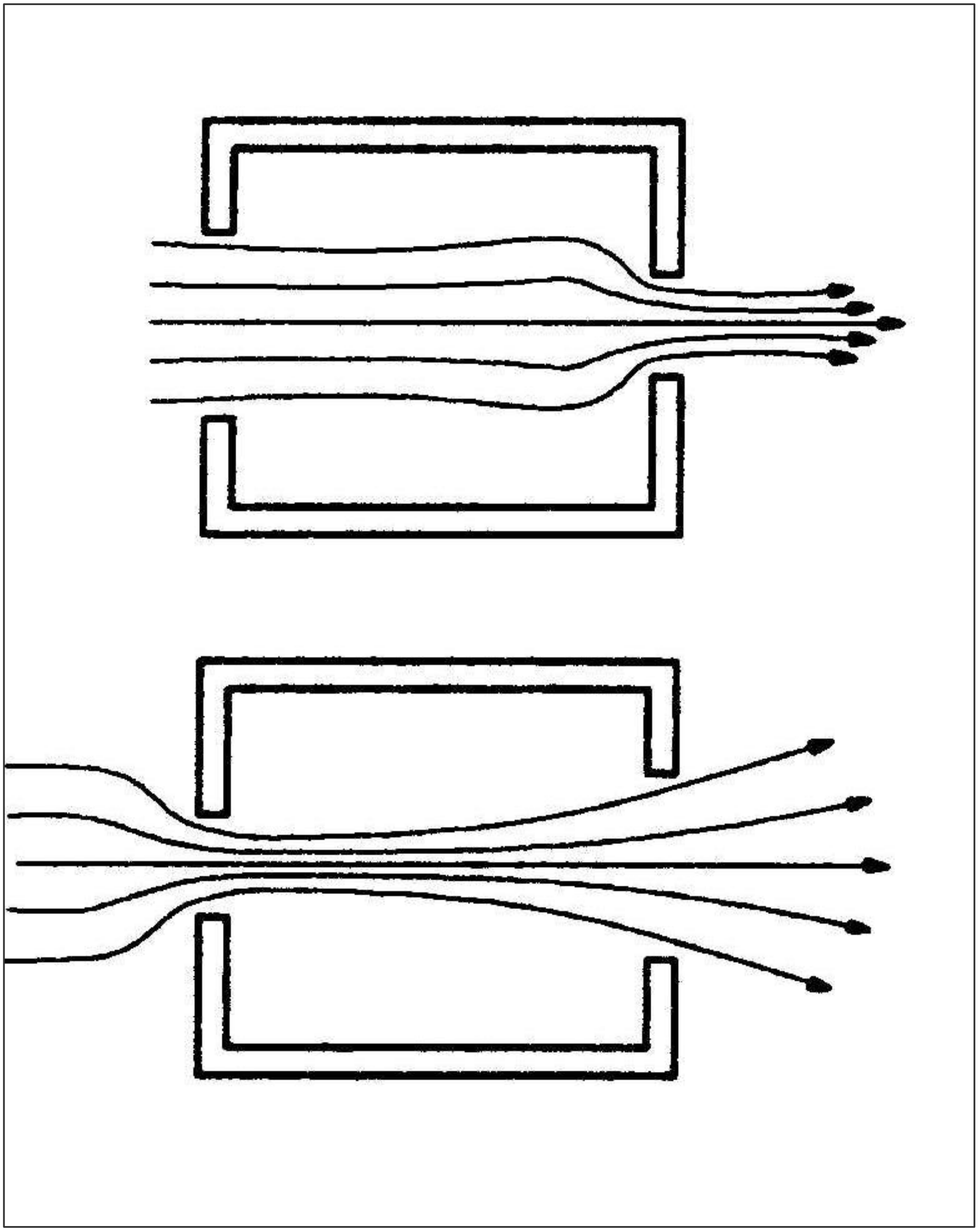
Determinants of airflow for comfort ventilation. The problem of summer comfort in warm humid regions requires that breezes must pass through the building to remove any build-up of warmed air, particularly under the roof and ceilings. In addition, the airflow must pass over occupants, at sufficient velocity to aid in the evaporation of perspiration, and so extend the perceived comfort zone to higher temperatures. Similarly in a museum, airflow must reach all parts of the space to aid mould control on collections. Building and landscape design should direct air movement in desired directions, and often enhance the available velocity of the available breeze.

Determinants of air velocity. The principles are best illustrated by reference to a simple building plan or section. Firstly, to have effective ventilation, an outlet as well as an inlet is required. The factors which then affect the speed of airflow through the building are:

- the ratio of outlet to inlet opening sizes; and

- the degree of obstruction to the flow.

Fig. 7.4. Air velocity is greatest when the inlet is smaller than the outlet

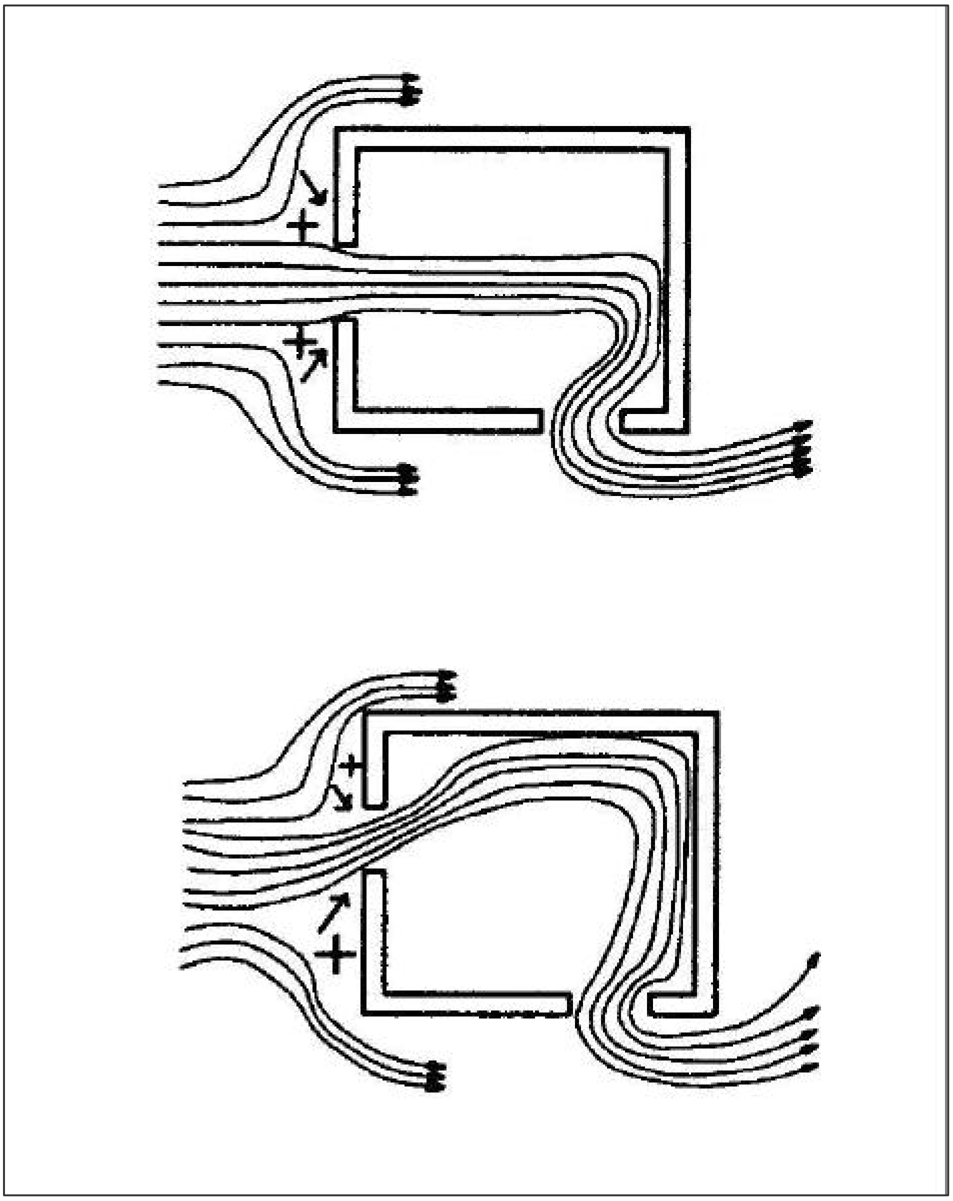


For maximum air speeds within the building the outlet should be greater than the inlet (Fig. 7.4.). This situation is analogous to the spillway of a dam through which the water rushes from a lake that is hardly moving at all. When the inlet is larger than the outlet, this spillway effect is outside the room, whereas when the inlet is smaller, it occurs within the room.

Determinants of airflow direction. Moving air has momentum and will keep moving in a particular direction until turned by pressure differences. This makes the motion of air very difficult to predict in detail but some practical approximations may be derived.

Note in the diagrams (Fig. 7.5.) that the airstream continues some distance into the room before turning to seek the outlet.

Fig. 7.5 Airstream direction is determined by the position of the inlet opening



In addition the direction of air entering a room is 'steered' by pressure difference between the two sides of the opening. In the top diagram (Fig. 7.5.), the pressure distribution on the windward facade is approximated. On the lower diagram, an asymmetrically positioned opening will have a more elevated pressure on one side of the inlet opening, than on the other. This pressure difference influences the direction of the incoming stream of air, as shown.

This effect may be used to ensure that air movement occurs where it is required, for instance near the floor in the occupied zone of the room. Attention therefore must be given to the location of the opening in the facade, and the design of window surrounds and secondary openings, which may modify the pressure distributions. Where the location of openings in the facade cannot be determined by these considerations, the air distribution in the room may need to be solved by physical deflection of the air-stream at the window plane, such as by louvres.

The location of outlet openings is not critical, as long as they are in an area of lowered pressure. The maximum air speed is obtained when the airstream does not lose too much momentum by many abrupt changes in direction. This is the basis of the requirement for 'cross-ventilation' in traditional architecture for warm humid climates. Cross-ventilation favours simple, one room deep plans.

Air quality. Low levels of outdoor air supply (whether natural or mechanical) to minimise the intrusion of urban air pollutants needs to be used judiciously in each building, according to:

(a) the degree to which levels of urban air pollution are high;

(b) the presence of indoor pollutant sources, which may lead to high indoor pollutant levels at low ventilation rates; and

(c) the level of occupancy of the building, from the perspectives of both supplying sufficient 'fresh' air for the health and comfort of occupants, as well as removing pollutants generated by occupants themselves.

The degree to which building ventilation can be reduced might be generalised according to the level of carbon dioxide (exhaled from occupants) achieved in the building. Outdoor carbon dioxide levels are typically 400 ppm. One guideline used by many building authorities is that if indoor levels exceed 800–1000 ppm maxima during days of occupation, ventilation is inadequate for health and comfort relative to the number of occupants.

7.1.2.5. Building elements as moisture buffers

Most building materials are porous and/or hygroscopic and store large amounts of water. In fact, the quantities of water that building materials store are hundreds of times greater than the quantities of water vapour contained in the air which the materials surround. A building typical of a historic house museum may contain 5kg of water in the enclosed air, and 2#000kg of water in the building materials.

The use of porous materials in walls and ceilings is an unappreciated aid to maintaining constancy of relative humidity indoors and deserves the attention of architects and engineers. Hygroscopic walls and ceilings give substantial stability to the indoor relative humidity (RH) in rooms which are ventilated at less than about one air change per hour. A few centimetres of material are sufficient to buffer the daily RH cycle, about 40 cm of wall will buffer the annual cycle of RH in a room with about 0.1 air changes per hour.

The implications are obvious. At the scale of buildings, or in the case of store rooms housing a significant amount of organic material of large surface area, the relative humidity of the air will be dependent on the moisture content of the materials, rather than the other way around. Furthermore, if such spaces have limited opportunity for exchange of air with the ambient environment, the relative humidity will be buffered by the objects contained, because the materials will desorb water with rising the temperature. Temperature changes are a greater force in determining moisture content than humidity changes in the surrounding air.

Clearly, therefore, humidity buffering by building materials is a key phenomenon in passive environmental control for museums. Unfortunately, no research on humidity buffering in warm climates appears to have been undertaken to date.

7.1.2.6. Natural light

The effect of light on stored and displayed objects is well documented, and is discussed in section 3.3. Illumination levels required for storage are governed only by the requirement for working with the materials in question. General lighting may therefore be quite low, and supplemented by intermittent artificial task lighting. Lighting for display poses greater difficulties, and the discussion of architectural control of illumination appears to be the subject of fashion as much as reason (see also sections 10.1.2. and 10.2.2.).

The levels of 'safe' illumination for most materials are very much lower than the externally available natural light, which in addition contains excessive UV components (section 4.2). However, to more usefully discuss natural lighting, it is important to distinguish between sunlight and daylight.

Sunlight is several orders of magnitude higher intensity than light from other parts of the sky. It probably has no place in any part of a space used for the conservation of sensitive materials. This applies to some degree even to reflections from sunlit surfaces, whether within or external to such a space. In warm climates, the coincidence with the need for shading for thermal control should make exclusion of solar radiation an absolute requirement.

Daylight is light from the remainder of the sky hemisphere, excluding the sun’s disk. Daylighting may be usefully deployed in even sensitive display areas, and aversion to it is probably unreasoning paranoia on the parts of some curators and conservators. Daylight is the most economical source for general illumination of the building interior and is of generally favourable colour balance for the display of most objects. Even when examined in terms of control of associated heat loads, it has a higher luminous efficiency (lumens/watt) than almost all artificial sources.

Daylight admitted by conventional windows falls off in intensity so rapidly with distance from such openings (the 'inverse square law' dictates that doubling the distance quarters the illumination level), that limitation of illumination to given 'safe' levels is largely a matter of display layout. The fast decay of daylight levels from openings to interiors may itself be used to differentiate circulation from display areas, and to assure levels of general illumination to avoid impressions of 'gloom'.

Simple reflections of daylight by white painted surfaces remove over 80 per cent of all harmful UV components. Of course, lux levels are also reduced by the reflections, but in approximately the inverse proportion. If a guaranteed double reflection can be arranged, the resulting illumination will have UV/lux ratio reduced to approximately 1/16 that of the original daylight.

In principle, this means that as long as exclusion of sunlight is guaranteed by a combination of orientation, shading and detail design, and daylight is admitted by openings designed to achieve reflection off painted surfaces, then buildings may be designed to exploit daylighting for display without compromising conservation requirements, and without resort to expensive and degradable filters.

7.1.3. The principle of ‘layered’ control

As mentioned previously, there are some limits to the application of passive environmental control to conservation objectives, especially in hot humid climates. However, in all climates, the extremes of the external environment can be progressively modified.

The principle of 'layered control' is well known to curators and conservators, and is usually applied in museums for the progressive reduction of RH variation or air pollutant concentration as you move from outside, to interior space, to showcase. It relies first and foremost on restricting the degree of air exchange between each 'layer' of space, with the rate for a showcase measured in changes in a day, rather than air changes per hour.

The same principle can be applied to all environmental variables to some degree, except that other variables than air exchange are also employed. Each of the following constitutes an incremental layer of protection:

- appropriate siting;
- reduction of loads on the building;
- layout planning to place the least vulnerable spaces to the greatest exposure, in order to 'isolate' rather than 'insulate' vulnerable spaces; and
- the use of local controls, such as showcases or other microclimates.

These principles are the framework of passive design strategies for different climates, described in section 8.