Chapter 4
Passive Design Technologies

4.1 Introduction

The term ‘Passive Design’ here refers to design strategies, technologies and solutions that effectively take advantage of the environmental conditions outside the building to maximise the energy and cost savings while ensuring the core building facilities and provisions (such as indoor comfort, safety, health, etc.) are not compromised. The environmental conditions can provide several advantages or disadvantages to the building such as the following:

- *Day lighting*: can reduce the energy used for artificial lighting but excessive and improper exposure may result in glare and other forms of visual discomfort
- *Natural ventilation*: can reduce mechanical ventilation energy to move air around but can result in hygiene issues and over-cooling in cold climates
- *Natural cooling*: to reduce the need for excessive air-conditioning or mechanical cooling in hot climates
- *Natural heating*: to use the energy from the sun to provide heat indoors in cold climates instead of providing excessive artificial heating. But this needs to be managed in hot climates to reduce air-conditioning energy use
- *Shading*: (from trees or neighbouring buildings) can reduce heat from direct sun exposure in hot climates but can obstruct views and natural light and heat in cold climates.

The key elements of passive design are:

1. Building location and orientation on the site
2. Building layout and massing
3. Building envelope (windows, walls, roof, insulation and shading).

These passive design elements (as summarized in Fig. 4.1) are massive levers to achieve a high performance building in the early stages of the building design process. Once fixed, it’s often very difficult and costly to change these elements as

N.Y. Jadhav, *Green and Smart Buildings*, Green Energy and Technology,
DOI 10.1007/978-981-10-1002-6_4

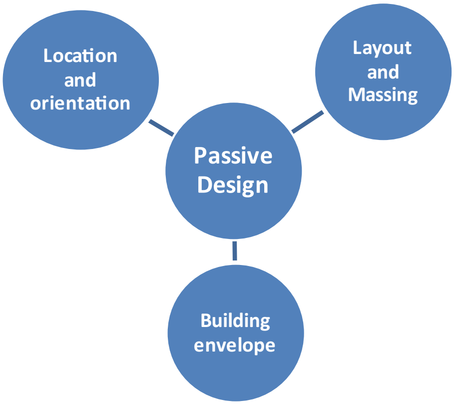


Fig. 4.1 Key elements of passive design for green buildings

the building development progresses. After construction it is almost impossible to change some of these elements such as the orientation and massing without having a drastic and dramatic impact on the project costs and timeline. Let us consider these elements in more details and understand the associated key terminology and parameters before jumping into the technologies.

4.2 Building Location and Orientation

The location of the building on the site and its orientation can have a significant impact on its performance, considering that it can impact the following:

- The amount of sun (light and heat) a building receives
- The intensity of wind (breeze and ventilation)
- Access to views
- Access to transportation options and other site provisions
- Impact on or from neighbouring buildings.

The amount of sunlight and heat (solar heat gain) received by the building is often a key factor in determining the orientation of a building (see Fig. 4.2). Depending on the geographical location and outside weather conditions, this might mean different things for different designs. e.g. in cold climates with mild summers, it might be desirable to get more sunlight and solar heat gain in order to reduce the use of artificial lighting and heating. Whereas, in a tropical weather, its bets to avoid solar heat gain in order to reduce the amount of energy used for air-conditioning. However, it might be also desirable to harness the sun for solar energy generation.

It is also important to consider the surrounding site topography and elevation as that affects the wind conditions. e.g. a building at higher elevation is likely to have higher and more consistent wind conditions and buildings on the leeward side of a hill could produce stagnant wind conditions irrespective of the orientation

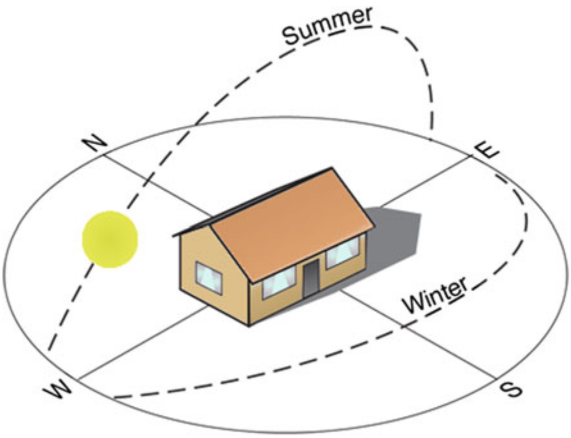


Fig. 4.2 Considering the sun path to decide building orientation (Autodesk 2015)

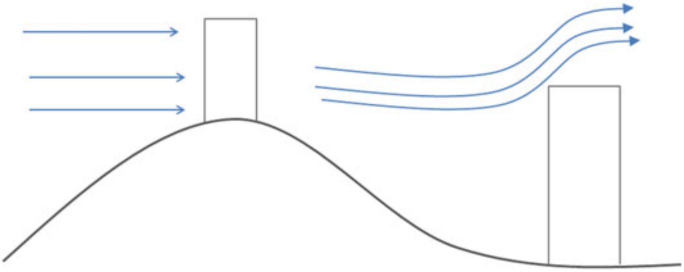
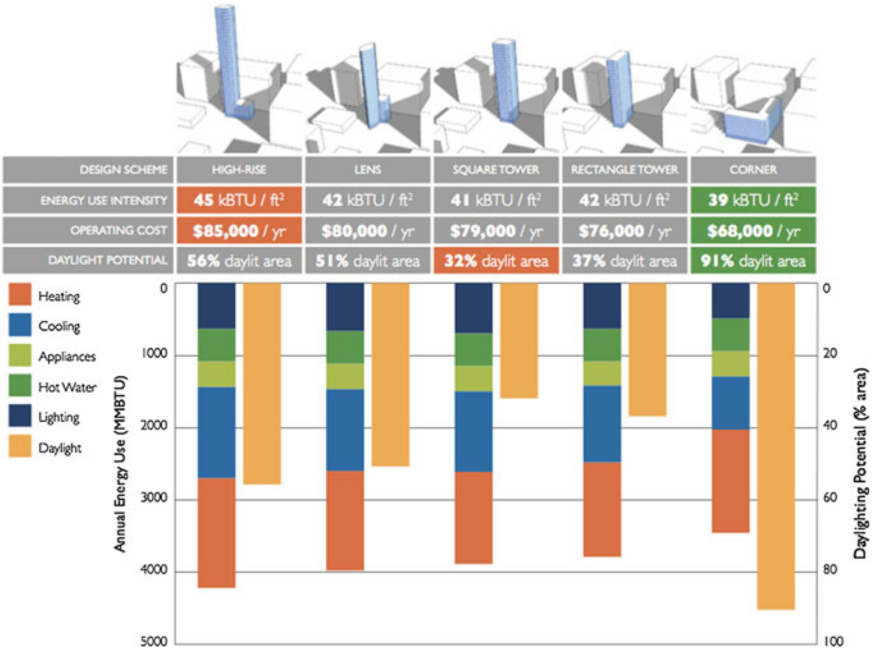


Fig. 4.3 Location of building resulting in different wind conditions

(see Fig. 4.3). The wind conditions can have a significant impact on energy use of the building especially in hot weather conditions where a naturally ventilated building can achieve comfortable conditions indoors without the excessive need for cooling or air-conditioning. The wind considerations (wind speed and direction) would also affect the building massing and location of certain equipment within the building considering the wind draft and wind load.

4.3 Building Layout and Massing

"Massing" is the architectural term used when determining the overall layout (e.g. compact or spread-out), shape (e.g. square, rectangle, oval), size (e.g. height, length, width) and form factor (more solid or porous with cut-outs) of the building. Massing choices depend on the project specifics such as the project site and its goals. It should be optimized in the early stages of the building along with its



DESIGN SCHEME	HIGH-RISE	LENS	SQUARE TOWER	RECTANGLE TOWER	CORNER
ENERGY USE INTENSITY	45 kBTU / ft²	42 kBTU / ft²	41 kBTU / ft²	42 kBTU / ft²	39 kBTU / ft²
OPERATING COST	$85,000 / yr	$80,000 / yr	$79,000 / yr	$76,000 / yr	$68,000 / yr
DAYLIGHT POTENTIAL	56% daylit area	51% daylit area	32% daylit area	37% daylit area	91% daylit area

Fig. 4.4 Massing options and implication on building performance (Sefaira 2013)

location and orientation. Successful massing for green buildings would help to reduce energy loads for the building by leveraging on the natural effects such as the wind flow patterns and the sun path.

Apart from reducing energy use, a good massing and orientation can also help in rainwater harvesting, integrating the building with urban planning provisions, reducing material usage and in protecting ecologically sensitive elements such as greenery, trees and ponds. Modelling and simulation tools as described in the earlier chapter can be used to assess the performance of the building with various orientation and massing choices. Figure 4.4 shows the impact of different massing options on the building's energy use intensity, operating costs and daylight potential.

4.4 Building Envelope

The building envelope is the 'skin' of the building. In simpler terms it is the is the physical separator between the exterior and the interior built environment (see Fig. 4.5 for a simple illustration of the building envelope). The key components of the building envelope are as follows:

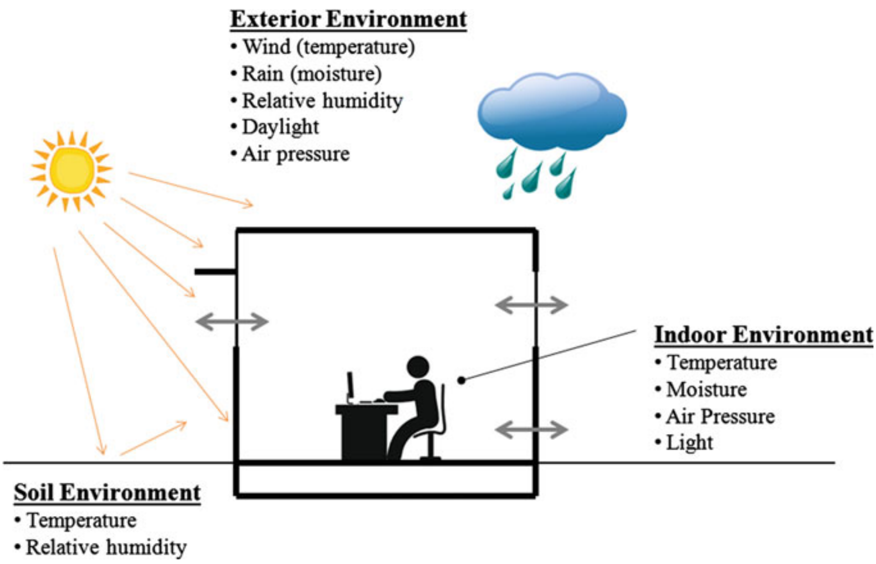


Fig. 4.5 Building Envelope and its interaction with the outdoor environment

- Roof: the covering on the uppermost part of a building
- Wall: the vertical structure connecting the roof and floor
- Floor: the bottom surface of the building or the walking surface
- Fenestration: openings in the structure such as windows, skylights and doors. When that opening is covered with a translucent or transparent surface (like glass), it's called glazing.

The choice of the building envelope is governed by the climate, culture, aesthetics and available materials. It has a significant impact on the performance of the building as it can determine the amount of sun light/heat and air ingress in the building. The choice of materials used for the building envelope also largely determines its carbon footprint and environmental friendliness.

In order to assess the performance of the building envelope, it is important to understand the material properties of the building envelope components such as their insulation, thermal resistance, heat gain coefficient, air infiltration and visual light transmittance.

4.4.1 Insulation

Insulation is the material that provides resistance to the transfer of heat through the building envelope. Insulation performs a critical function in building design because it enables spaces to avoid excess heat gain from outside and to retain the heat they have inside. Thus is helps to passively influence the heating or cooling energy used by the building.

Insulation is designed to prevent or provide resistance to heat transfer due to conduction (when materials are touching each other) and radiation (when there is no direct contact but an air-gap in between). The 'R-value' of the insulation material is a parameter that measures its resistance to conduction (high R-value means high thermal resistance). The resistance of the insulation material to radiative heat transfer is measured by its property termed as 'emissivity' (low emissivity means high resistance and high reflectance of radiative heat). A good insulation material used for a green building design hence should ideally have a high R-value and a low emissivity.

The thermal conductance through fenestration is a measured using the 'U-value' that specifies the rate of heat transfer per unit area per unit temperature difference between the hot and cold side. A lower U-value means lower heat transfer and hence better insulation from the fenestration element such as window, skylight or glazing. U-value is sometimes measured for the glazing only or it can be also specified for the entire window or skylight assembly. It depends upon the type of glass used for the glazing, the number of panes and air-gap in between, glass tinting, and reflective coatings.

4.4.2 Solar Heat Gain Coefficient (SHGC)

The Solar Heat Gain Coefficient (SHGC) is a ratio of the heat transmitted through the building envelope into the building to the heat that is reflected away. SHGC is a dimensionless parameter and can theoretically range from zero to one, with one representing that all of the heat being transmitted through the envelope, and zero representing none of the incident solar heat being transmitted inside. A low SHGC would be desirable for buildings with high cooling load (e.g. tropical and hot climates), whereas a high SHGC would be beneficial for buildings with passive heating requirements (e.g. cold climate conditions).

4.4.3 Infiltration or Air Leakage

Infiltration or air leakage is caused by air entering or leaving the building due to unintentional gaps in the building envelope. The outside air infiltrated into the inner space would cool or heat interior spaces through convection and make the envelope insulation redundant. The air leakage from inside to outside would result in energy wastage and overload on air treatment facilities such as heating or cooling as the treated air would escape to the surroundings instead of heating or cooling the space.

Infiltration or air leakage can be a problem for the overall building performance as it directly affects heating and cooling requirements in buildings. The severity of its impact however depends on the surrounding climatic conditions.

In cold climates, where the temperature difference between outside and inside can be significant, infiltration of outside air can cause huge energy penalties for the building. In hot climates, as the temperature difference between the outside and inside is low, infiltration will only moderately affect the energy performance. In moderate climates, infiltration can in fact be beneficial due to the natural ventilation caused by the infiltrated air that can reduce the energy for cooling, especially for spaces with high internal loads.

4.4.4 Visible Light Transmittance (VLT)

The percentage of visible light that passes through a window or glazing material is characterized by the parameter known as the Visible Light Transmittance (VLT). An opaque wall would have a zero VLT (0 %), whereas an unobstructed and empty facade opening would have a 100 % VLT. This property only measured the light in the visible portion of the spectrum (and not infrared light). A properly designed glazing unit with high VLT can reduce the electric lighting load and its associated cooling load.

4.5 Building Envelope Technologies

4.5.1 Shading

Shading are simple envelope attachments that can prevent the heat and glare caused by direct sunlight through windows. They are also helpful in reducing the direct sunlight incident on walls and roofs so that the building design is not overly reliant on insulation or high performance glazing in hot climates. Shading fixtures can be either provided inside the space or applied from outside and each arrangements have their own benefits and disadvantages.

4.5.1.1 External Shading Fixtures

An exterior fixture such as the horizontal overhangs (see Fig. 4.6) or vertical fins are the most common shading devices used in buildings. While horizontal overhangs are good for cutting of overhead sun exposure, vertical fins are useful in avoiding low-angled sun. Sun shading systems can be designed so as to provide great architectural impact as well as being highly functional. Shading systems now

Fig. 4.6 Photo of a building with exterior horizontal shading fixtures (Levolux 2012)

come in a great variety of materials such as glass, metal, wood, acrylic and fabric louvers and the choice depends on the effectiveness in the given climate and their architectural integration.

The shading dimensions (height and width) can be calculated in such a way as to allow the sunlight and heat into the building at particular time of the day in the year (e.g. during winter when the sun angle is low), while rejecting it at other times (e.g. during summer when the sun angle is high). Both these scenarios would minimise the heating and cooling loads of the building. This is the benefit of smart passive building design through the apt use of weather and climatic information coupled with simple envelope fixtures.

4.5.1.2 Motorized Internal Shading Devices

Internal shading devices such as roller or Roman shades or venetian blinds are commonly found in homes and commercial spaces and occupants can control or operate them easily. It can also be motorized and movable with automatic controls that are based on weather conditions and sunlight sensors or on fixed daily operating programs. Motorised and automatic internal shading can be an effective way to adapt to external conditions while ensuring occupant comfort.

4.5.2 Cool Roofs and Coatings

Cool roofs use materials with high solar reflectance (high albedo) that are able to reflect the sunlight that a conventional roof would otherwise absorb as heat. The heat absorbed by the roof would result in indoor discomfort or higher costs for cooling in warm climates. While insulation slows the transfer of heat into the building due its high resistance to conduction (high R-value), it does not eliminate the source of the heat gain. Cool roofs can reduce the need for excessive insulation in hot climates by enhancing the ability of the roof to reject solar heat. Figure 4.7 shows the effect of cool coating applied on a building in the hot tropical weather of Singapore.

In several other studies done, it is also proven that cool roofs absorb much less heat as compared with traditional dark-colour roofs as they are able to reflect the

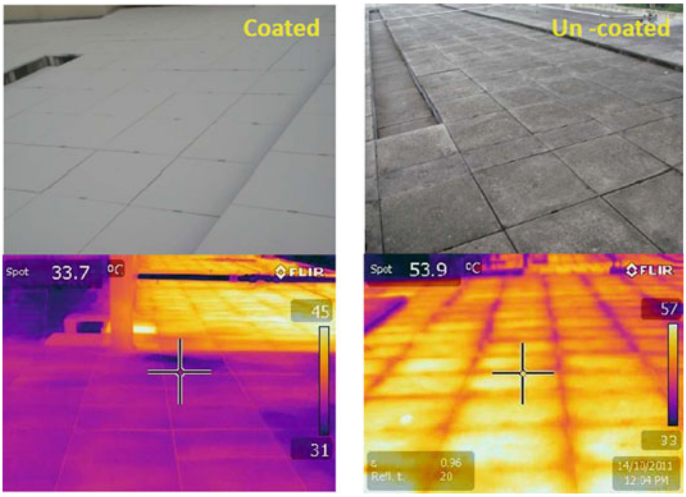


Fig. 4.7 Thermal imaging study in Singapore showing that cool coatings can reduce the surface temperature by more than 20 °C (*Source* ERI@N, Singapore 2013)

sunlight back into the sky (Urban and Roth 2010). The effectiveness of cool roofs is measured by the following properties:

1. Solar reflectance: measures the ability to reflect sunlight and is the ratio of the sunlight reflected to the solar radiation that is absorbed. It is also known as albedo. A solar reflectance value of one represents total reflectivity (high albedo) and a value of 0 indicates that the roof surface absorbs all solar radiation.
2. Thermal emittance: measures the ability to emit or release absorbed heat and is the ratio of the heat emitted to the heat absorbed. It is usually expressed as a decimal fraction between 0 and 1, or as a percentage value.
3. Solar reflectance index (SRI): measures the overall ability to reject solar heat and incorporates both solar reflectance and emittance. A standard black surface has a SRI of zero and a standard white surface has a SRI of 100.

Cool roofing materials such as white thermoplastic membranes typically have a solar reflectance of 80 % and thermal emittance of at least 70 %. This is significantly higher than asphalt roofs, which are able to only reflect up to 26 % of solar radiation typically. Stainless steel roofs also have a very high solar reflectance index (SRI) of 100–115, while the SRI of a perfect mirror is approximately 122 (CRRC 2015). Any roof surface can also be made reflective by applying a solar reflective coating. These coatings are typically paint formulations that achieve a very high SRI and are sometimes referred to as ‘cool paints’.

The Cool Roof Rating Council (CRRC) has created a rating system for measuring and reporting the solar reflectance and thermal emittance of roofing products. This system has been put into an online directory of more than 850 roofing products and is available on the web at: http://coolroofs.org/. It should be noted that although cool roofs are helpful in achieving cooling energy savings during the hot summer, it can erode the benefits of solar heat absorption during cold winters. Thus the overall benefits and annual net energy savings due to cool roofs need to be evaluated carefully for the particular climatic conditions.

4.5.3 High Performance Insulation

Insulation usually comes in different forms as follows (DOE 2015):

(a) Battings or blankets: usually made of fibreglass or rock wool (mineral fibre), can be installed in form of batts or continuous rolls that are stuffed into spaces between studs or joists.
(b) Loose-fill: loose fibres or rock wool, fibreglass or cellulose that are filled or blown in along with adhesive materials into building cavities. They can offer a firm fit and avoid air infiltration along with resistance to heat transfer.
(c) Foamed in place: mostly polyurethane, phenolic or cementitious materials that are sprayed directly into cavities where they are allowed to expand and fully seal the cavity. They offer a good air barrier and also have high R-values.

(d) Rigid board: plastic polyurethane or expanded/extruded polystyrene boards that are mechanically fitted on to the surfaces such as exterior walls, foundation and stem walls, concrete slabs and ceilings. They also provide structural strength while being low weight with high R-values to offer good thermal as well as acoustic insulation.

(e) Reflective films: radiant barriers that are mostly made out of aluminium foil with paper, cardboard or plastic backing that is integrated into housewrap or into rigid insulation boards. they are most effective in hot climates to reduce summer heat gain.

(f) Structural Insulated Panels (SIPs): prefabricated insulated structural elements that can be used in the building envelope system (walls, ceilings, floors, and roofs). They are made in a factory and shipped to job sites, where they are connected together during the building construction. They provide superior and uniform insulation compared to more traditional construction methods (stud or "stick frame"), offering energy savings of 12–14 % (DOE 2015).

4.5.3.1 Sandwich Walls

Sandwich walls or Sandwich panel claddings typically consists of two aluminium skins with a polyurethane (PU) or mineral wool core forming a light-weight cladding panel with very good insulating properties (see Fig. 4.8 for illustration of a sandwich wall panel). In some cases, the metal cladding can be also made of light weight material through perforations that allow air-flow through. They offer external insulation and reduction in solar heat gain for opaque walls. They can also be integrated as architectural enhancement and can help the building skin weather against rain and excessive heat and light exposure.

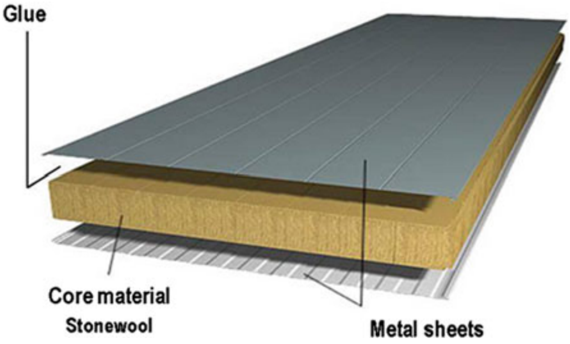


Fig. 4.8 Illustration of a sandwich wall panel used in building insulation

4.5.3.2 Thermal Insulation Plaster

Compare to conventional cement sand plaster, the thermal insulation plaster helps to cut down the heat transfer from the exterior to interior of walls and vice versa. It consists of materials that are mixed with cement, such as styrofoam beads, to enhance the insulation properties of cement, while being easy to apply. It can also save the use of sand in construction and provide a lightweight application that can enhance the fire resistance properties and recyclability. Figure 4.9 shows application of a thermal insulation plaster on the exterior walls of a building.

4.5.4 High Performance Glazing

Windows and more typically glass windows (i.e. glazing) are important element of the building envelope and also offer significant energy saving opportunities. As described earlier in Sect. 4.4, the glazing energy performance can be determined by three main properties: insulating performance (U-value), solar heat gain coefficient (SHGC), and visible light transmittance (VLT or VT).

In addition to conventional single-pane and double-pane windows or glazing units, there are now newer technologies available that can significantly improve their performance on the above factors. These technologies are multiple pane glazing (triple pane, quadruple pane, etc.), inert gas fills, Low-E (low emittance) glass coatings, selective transmission films and adaptive glazing.

Fig. 4.9 Photo showing application of a thermal insulation plaster (MagorTherm 2015)

4.5.4.1 Multi-pane Windows and Gas Fills

The insulating performance (i.e. U-value) of glazing units can be improved significantly by reducing the convective flows within the unit by sub-dividing the air-space in between and adding more panes (see Fig. 4.10 for a simple illustration). These interior panes can often be simply thin films while the inner and outer side panes are structural glass. The spaces between window panes can be filled with gases that have the ability to insulate better than air. Gases such as argon, krypton, sulphur hexafluoride, and carbon dioxide are generally used for this purpose. These gases have much lower conductivity than air and can greatly reduce heat transfer by convective currents, resulting in a lower overall U-value for the glazing unit. As a resulting effect, the inner surface of the glass can be maintained at a temperature closer to that of the indoors, thus enhancing comfort and reducing cooling/heating loads.

4.5.4.2 Low-E Coatings

Low-E (low emissivity) glass coatings are made from microscopically thin and transparent layers of metal or metallic oxide (such as silver oxide) that can be designed to reflect UV and infrared radiation while transmitting light in the visible

Fig. 4.10 Simple illustration of a triple glazing window pane

wavelengths. Low-E coatings can be used in combination with tinted glass in order to avoid glare issues due to too much visible light transmission, while cutting significantly on solar heat gain.

4.5.4.3 Selective Transmission Films

'Spectrally selective' window films selectively filter solar radiation by allowing visible light in while blocking heat (IR) and UV radiation. They are made of sophisticated combination of layered optical filters combined with nano particles to achieve the desired effect. These films appear mostly clear and are mostly effective in reflecting even far infrared radiations that are emitted by warm objects within the space. Thus these type of films can be effective in both summer (to cut long-wave infrared radiation from sunlight) and winter (to preserve heat from warm objects inside the space).

4.5.4.4 Adaptive Glazing

Adaptive glazing systems have the ability to change their properties such as the visible light transmittance and solar heat gain coefficient, based on the outdoor conditions or on user on demand. These adaptive glazing technologies offer significant advantages over the static performance glazing systems described above as they can cover all weather conditions and any special requirements from the users or occupants of buildings. This is achieved by incorporating coatings and materials between two glass or plastic sheets that are capable of modulating the optical transparency and other properties in response to an external trigger.

Thermochromic Glazing: Thermochromic glazing are sensitive to temperature and at high temperatures they can turn from being clear to become dark or translucent, reducing their VLT and SHGC. It generally consists of thermotropic materials such as hydrogels, polymer blends, and block copolymers. At low temperatures, these materials are homogeneously dispersed in a matrix, thus minimizing light scattering and appearing clear. As the temperature is increased (beyond their switching threshold), a phase separation between the thermotropic domains and the matrix occurs abruptly. This results in scattering centres that reflect the light and they change appearance to be translucent. It should be noted that the phase switching only happens beyond a particular temperature threshold and sometimes if this threshold is not reached despite the intense solar radiation that is incident on it, the desired effect will not be achieved.

Photochromic Glazing: Photochromic glazing turn from being clear to become dark based on the light intensity. This feature can be commonly found in adaptive sunglasses. This technology is not yet fully scaled-up successfully at the level of using it for large commercial windows. As the switching is based on the light intensity, it might result in inappropriate action as the solar heat is not always proportional to the light that strikes the window, especially in case of low angled sun.

Electrochromic Glazing: Electrochromic glazing change their optical transparency and other properties by changing its colour or opacity when an electric field is applied. Once the field is reversed the optical properties are also restored back. In these type of windows, a thin, multi-layer assembly is sandwiched between the glass panels. The outside layers of the assembly are transparent electronic conductors that enclose a counter electrode layer and an electrochromic layer, with an ion conductor layer in between. When a voltage is applied across the conductors, the ions move from the counter-electrode to the electrochromic layer and cause the assembly to change colour. Reversing the voltage moves ions from the electrochromic layer back to the counter electrode layer, restoring the device to its previous clear state.

4.5.4.5 Thermal Breaks

Although the U-value of the glass can be improved with the above technologies, it's also important that the window frame does not conduct heat around the glass. Typically window frames that hold the glass are made of aluminium or other light-weight metals. Ideally, the metal framing should be 'thermally broken' to separate interior metal elements from exterior elements. Thermal break is nothing but an insulating barrier between the inside and outside of the window frame. Thermal breaks can be made from materials such as high density polyurethane resins or fibreglass. Figure 4.11 shows an illustration of the use thermal breaks in triple glazed window frames.

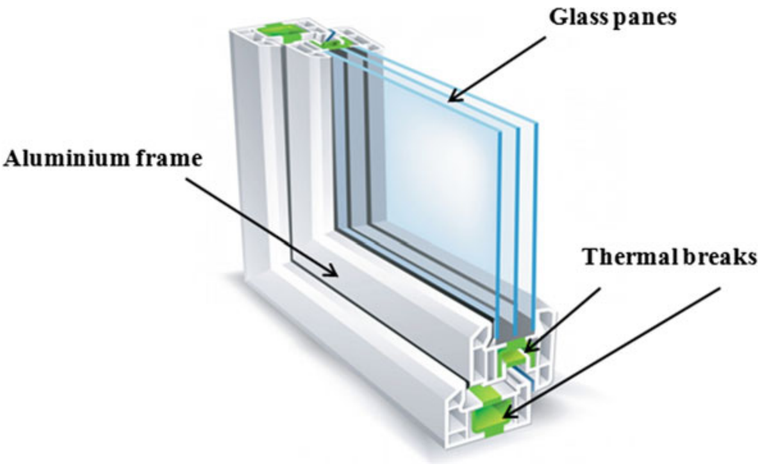


Fig. 4.11 Illustration of a triple glazing with thermal breaks

The thermal break must be a poor conductor of heat in order to avoid heat from moving from outside to inside and vice versa. It also functions as a structural element in holding the two metal profiles together. Thermal breaks are also good for sound absorption and insulation compared to metal, which can also conduct sound easily.

4.5.4.6 Overall Glazing Unit Performance

As seen in the above sections, the overall glazing energy performance not only depends on the glazing material and type of coating used, but also on the design of the whole window system, i.e. multiple glazing panes placement, frame, spacers, and the gas fill. To express the interaction of these components, the National Fenestration Rating Council (NFRC) has developed standards for rating the U-value (also known U-factor), SHGC, and VLT ratings of whole windows, including all of their components. Figure 4.12 shows an example of the NFRC label.

There are also software tools available that support the systematic evaluation of alternative fenestration systems. One such tool is COMFEN that is developed by the Lawrence Berkeley National Laboratory (LBNL). Similar to other modelling and simulation tools described in Chap. 3, this tool uses the Energy Plus simulation engine. The results from the simulations are presented in graphical and tabular format within the simplified user interface for comparative fenestration design cases to help users move towards optimal fenestration design choices for their project at hand.

U-factor U-factor ratings generally fall between 0.20 and 1.20. The lower the U-factor, the better a product is at keeping heat in. U-factor is particularly important during the winter heating season. This label displays U-factor in U.S. units. Labels on products sold in markets outside the United States may display U-factor in metric units.

Visible Transmittance (VT) is expressed as a number between 0 and 1. The higher the VT, the higher the potential for daylighting.

NFRC
National Fenestration Rating Council®
CERTIFIED

World's Best
Window Co.
Series "2000"
Casement
Vinyl Clad Wood Frame
Double Glazing•Argon Fill•Low E
ABC-X-1-00001-00001

ENERGY PERFORMANCE RATINGS

U-Factor (U.S. / I-P)	Solar Heat Gain Coefficient
0.35	0.32

ADDITIONAL PERFORMANCE RATINGS

Visible Transmittance	Air Leakage (U.S. / I-P)
0.51	0.2

Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information.
www.nfrc.org

Solar Heat Gain Coefficient (SHGC) is expressed as a number between 0 and 1. The lower the SHGC, the better a product is at blocking unwanted heat gain. Blocking solar heat gain is particularly important during the summer cooling season.

Air Leakage (AL) rates typically fall in a range between 0.1 and 0.3. The lower the AL, the better a product is at keeping air out. AL is an optional rating, and manufacturers may choose not to include it on their labels. This label displays AL in U.S. units. Labels on products sold in markets outside the United States may display AL in metric units.

Fig. 4.12 Example of a NFRC rating label to understand the energy performance of windows (NFRC 2012)

4.6 Passive Heating Technologies

Passive heating takes into account the energy of the sun to design for occupant comfort while reducing the energy used on mechanical systems for providing the same. Sunlight can heat a space via heat absorption in the solid walls or roof and also can enter the space through the fenestration, and heat interior surfaces. Some of the sun's light is long-wavelength infrared (IR) radiation, which is heat. In addition, the light of any wavelength absorbed by internal surfaces turns into heat in those materials. These materials then warm people in the room by conducting heat to them directly, by warming air which carries heat by convection, and by re-radiating their heat. This is all generally classified under the term 'solar heat gain'.

4.6.1 Massing and Orientation for Heating

Massing and orientation are important design factors to consider for passive heating. The cold climates, the sun's heat is desirable for 'free' heating and reducing the use of mechanical or electric heaters. Hence, as a simple strategy the building surfaces exposed to the sun's path can be maximised to harness as much heat as possible from the solar heat gain. The opposite will be true for hot climates, where the undesirable solar heat gain can be avoided by orienting surfaces and fenestration away from the sun path and using massing strategies get shading effects to avoid direct exposure to the sun.

It is sometimes however not that straight forward to implement the simple strategy as described above site constraints, natural ventilation and day lighting also need to be considered for massing and orientation. The exposure time and hour of the day is also important. For example, heat gain on the east side can be acceptable or even useful, because it happens in the morning after the cooler night, whereas heat gain on the west side is not desirable at the end of a warm day.

4.6.2 Thermal Mass and Phase Change Materials

Thermal mass in the building can store energy absorbed from the sun and release it slowly over time. Conversely, it can resist heating up too fast from solar radiation. It would be desirable to have building objects or materials with high thermal mass to absorb and retain heat, thus slowing the rate at which the space gets heated in the sun and cooled at night. In absence of any thermal mass, heat that has entered a space will re-radiate back and make the space overly hot when exposed to the sun. Also when the sun sets, the space can get overly cool when there is no thermal mass that has absorbed and retained the solar heat during the day.

In locations, with large differential temperature between the day and night (e.g. desert climate), the thermal mass can provide an effective mechanism to reduce mechanical heating and cooling loads. In locations that are constantly hot or cold throughout the day and night (e.g. warm tropical climates or sub-polar regions), the thermal mass may not be desirable as it can have a rather detrimental effect. This is due to the fact that all surfaces will tend to be at the average daily temperature of the surroundings, resulting in unwanted radiant gains or losses and hence occupant discomfort or huge energy penalties to counter the effect of thermal mass.

Thermal mass can be implemented in the building architecture as thick concrete floor slabs, water containers or tubes, and interior masonry walls with clay bricks or natural rock and stone. A large surface of interior thermal mass with direct exposure to sunlight is most beneficial for passive heating. Thermal mass can also be effective for cooling if the heat gain from the direct sun exposure can be effectively dissipated outside or to the ground without affecting interior spaces. However, such architectural implementations of thermal can lead to bulky buildings with excessive weight.

This problem of bulky thermal mass can be solved by using phase change materials to add thermal mass. These materials absorb and release thermal energy during the process of melting and freezing in form of latent heat. Common phase change materials such as wax and molten salts can be used for storing heat energy at appropriate operating temperatures. As a relatively large amount of heat is required for phase change at a given temperature, the phase change material acts as thermal mass that can absorb heat from hot surroundings and reject heat to cooler surroundings. The integration of phase-change materials in the building envelope can be achieved through micro-encapsulation and is a subject of ongoing research and development to achieve the right level of thermal mass effect at the right surrounding temperatures.

4.6.3 Trombe Walls for Passive Heating

A Trombe wall, named after its French inventor Felix Trombe, is a system for indirect solar heat gain and incorporates the thermal mass and glazing greenhouse effects in order to achieve passive heating. It is essentially a wall with high thermal mass and preferably dark in colour that can absorb the solar heat when directly facing the sun. It is placed behind a glazing with a small air space in between. Figure 4.13 shows an illustration of this concept. The glazing further traps the solar radiation like a greenhouse and increases the heat that is absorbed and stored in the wall. This heat can then be conducted slowly inward through the masonry. By including upper and lower air vents in the wall, the air convection and flow in the space can be enhanced, as air heated in the Trombe wall flows into the room at the top and cooler air from the room enters the wall system at the bottom.

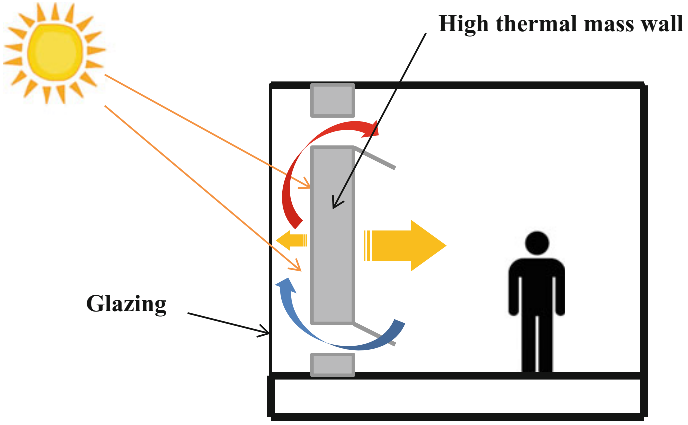


Fig. 4.13 Trombe Wall for passive heating with interior vents

Trombe walls can function as highly effective passive heating system and also can enhance the silence and privacy in the room compared to rooms heated by forced-air systems. They also require little space to operate and can be easily integrated into the building architecture to enhance occupant comfort in cold climates through passive heating alone.

4.7 Passive Cooling Technologies

Passive cooling is useful in providing a cooler and more comfortable indoor conditions through the use of natural energy sources. The main method of passive cooling is through natural ventilation and use of ambient air for cooling. There are various strategies to induce natural air flow and use natural elements to enhance indoor thermal comfort.

4.7.1 Natural Ventilation and Cooling

Natural ventilation uses natural outside air movement and pressure differences to passively cool and ventilate a building without the need for mechanical fans or air-conditioning system. For natural ventilation to be effective, it has to achieve the following:

1. Bring in enough volume of air to replace stale air in any space that may result in heat accumulation or accumulation of harmful gases/chemicals and odours.
2. Provide a wind speed that is comfortable for humans occupying the spaces or suitable for the activities carried out in the space.
3. Achieve temperatures and air quality, which are comfortable for the intended purpose of the space.

Often times, building designers and architects rely on natural ventilation only for spaces that do not have a continuous human occupancy or do not have needs for precisely controlling the indoor environment. Such spaces could be corridors, stairwells, toilets, atrium, etc. However, it's a good design practice to maximize the naturally ventilated spaces in a building as it can have a significant impact on its overall energy use. The following technologies could be used to enhance the natural ventilation effect in buildings.

4.7.1.1 Massing and Orientation for Natural Ventilation

Massing and orientation are important aspects of design in order to effectively channel outside air through occupied spaces by playing with the building's height and depth. Tall buildings can significantly improve natural ventilation as wind speeds are faster at higher altitudes. At the same time, tall buildings if oriented correctly can also reduce the sun exposure.

Through good orientation and massing, buildings can maximize the benefits from cooling breezes in hot weather and block undesirable wind in cold weather. This is site and geography specific, but most weather data will have information on prevailing wind direction and intensity. The wind rose diagram as shown in Fig. 4.14 is a good graphic to refer to understand the wind conditions at a specific site.

The Beaufort scale is a good guide to understand the wind effects on people and the building planners and designers can use this to achieve various wind conditions in naturally ventilated spaces to achieve the desired effects. As can be seen from Table 4.1, the desirable wind speed for natural ventilation in buildings typically should be in the range 2–3 on the Beaufort scale.

As a massing strategy, providing void decks at the ground floor, higher floor-to-floor heights and void spaces in between buildings (as shown in Fig. 4.15) will improve air flow through and around buildings. This also helps to mitigate stagnant air flow areas. This however needs to be controlled to avoid excessive wind flow and/or wasting space unnecessarily.

4.7.1.2 Openings for Cross Ventilation

While designing openings (doors and windows), architects and designers can plan for enhance natural ventilation by providing pathways for airflow through the structure. One common practice is to provide cross-ventilation by providing

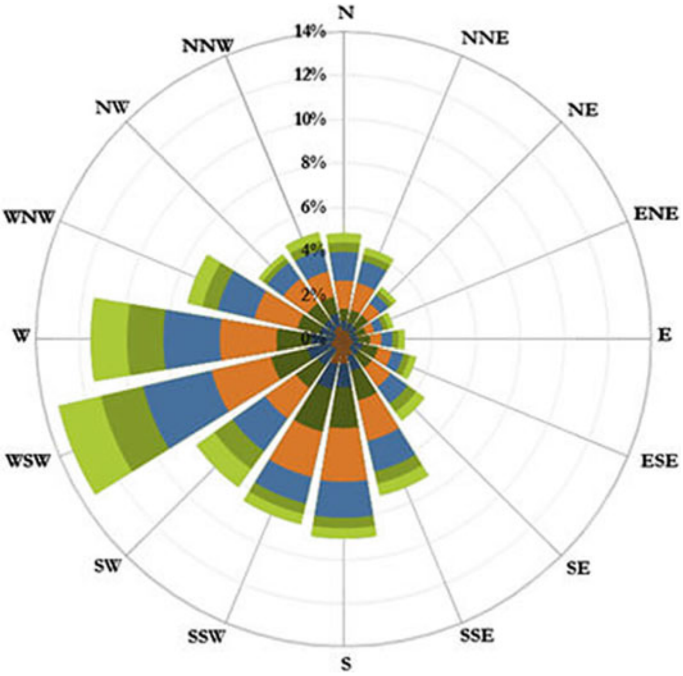


Fig. 4.14 Wind-rose diagram showing wind speed and direction statistics for a particular region

Table 4.1 Beaufort scale to understand effect of wind speed on human comfort (Penwarden and Wise 1975)

Beaufort scale	Type of winds	Wind speed (m/s)	Effects
1	Calm, light air	0–1.5	Calm, no noticeable wind
2	Light breeze	1.6–3.3	Wind felt on face
3	Gentle breeze	3.4–5.4	Hair is disturbed, clothing flaps
4	Moderate breeze	5.5–7.9	Raises dust, dry soil and loose paper–hair disarranged
5	Fresh breeze	8.0–10.7	Force of wind felt on body
6	Strong breeze	10.8–13.8	Umbrella used with difficulty, hair blown straight, difficult to walk steadily, wind noise on ears unpleasant
7	Near gale	13.9–17.1	Inconvenience felt when walking
8	Gale	17.2–20.7	Generally, impedes progress, great difficulty with balance
9	Strong gale	20.8–24.4	People blown over by gust

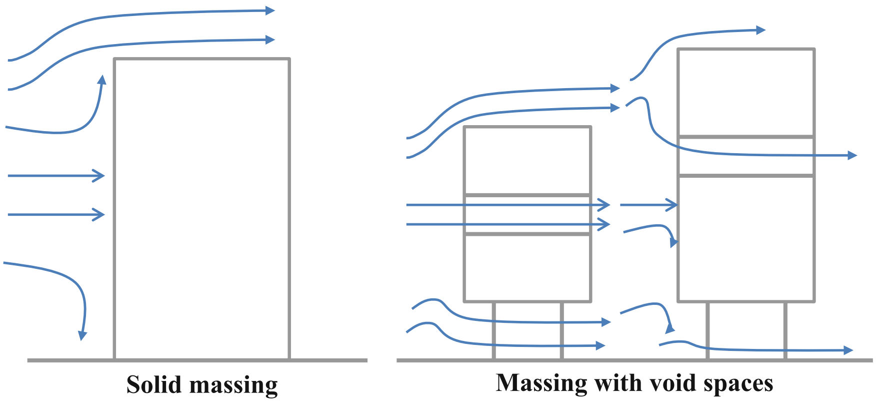


Fig. 4.15 Enhancing airflow through better massing and provision of void areas

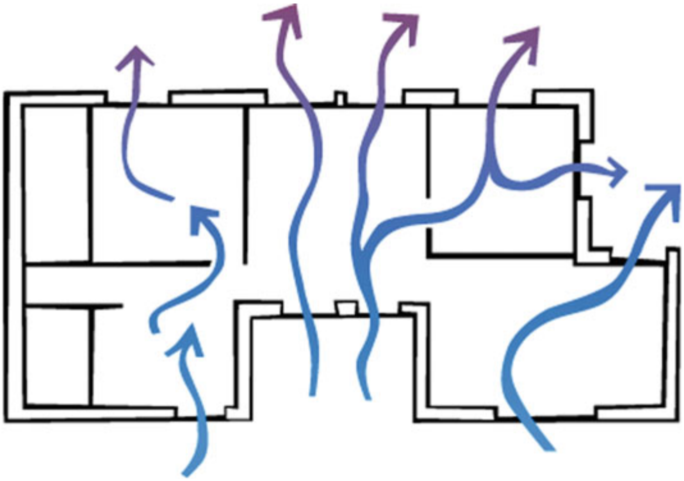


Fig. 4.16 Openings for cross ventilation can enhance natural air circulation

windows or vents across the other side of the building, often directly opposite to each other (see Fig. 4.16). While designing openings for large spaces, it's important to factor in air-mixing and circulation within the space and placing opening directly opposite to each other may create dead-spaces or stagnant spaces where there are no openings. This could be mitigated by providing openings across from, but not directly opposite each other.

To effectively utilize the pressure differential for better wind speeds, inlets should be placed at high pressure zones and outlets at low pressure zones. Pairing a large outlet with a small inlet increases incoming wind speed. While designing openings for natural ventilation, other weather conditions such as rain has also to be considered and that can be done by providing louvers that can block rain while providing the wind flow opening.

4.7.1.3 Wing Walls

Wing walls are architectural features that help in steering winds for enhancing the natural ventilation effect. They are built as vertical building envelope attachments that project outward next to a window or large opening in the building. Even a slight breeze against the wing wall can create a high pressure zone on one side and a low pressure zone on the other side. This pressure differential draws outdoor air in through an opening at one side of the wing wall where the pressure is high and out through the other where the pressure is low. Wing walls work well in sites with low outdoor air velocity and where the wind direction can vary considerably.

4.7.1.4 Stack Ventilation

The stack effect is the passive movement of air through the building by leveraging on thermal buoyancy i.e. hot air rising due to its lower density. Stack ventilation makes use of this effect by incorporating openings in the building envelope at substantial height to allow the warm air to escape from the top. This results in negative pressure at the bottom that can draw-in cooler air from an opening near the bottom of the building. In tall buildings, this can be achieved by connecting the airflow of different floors and channelling it upwards through vents, towers and chimneys. Stack ventilation can be designed to be an effective mechanism for passive cooling and avoiding mechanical cooling and ventilation in summer. In winter however, the high temperature difference between the building interior and exterior can be problematic and result in over-ventilation and heat loss. When temperature differences between outside and inside are low, it may not be so effective and can result in under-ventilation, especially for the upper floors.

4.7.1.5 Solar Chimney

Solar chimney works on a similar principle as the Trombe wall, but to enhance natural ventilation it uses the buoyancy and thermosiphon effect (stack ventilation). Solar heat gain warms a column of air trapped in between two walls, causing it to rise and pull new outside air through the building. In its simplest form, the solar chimney consists of a black-painted chimney. See Fig. 4.17 for illustration of this phenomenon.

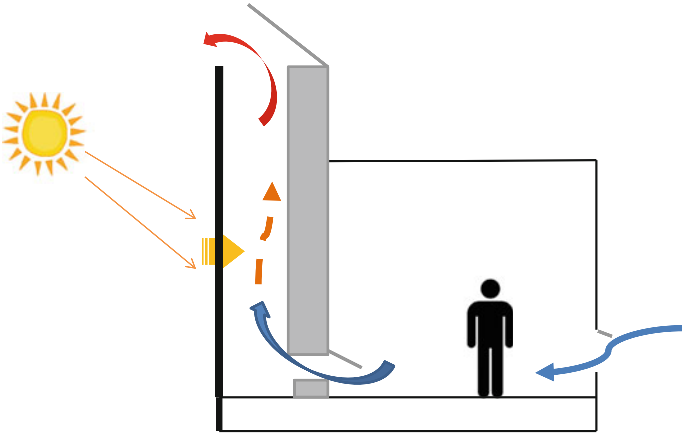


Fig. 4.17 Illustration of the Solar Chimney with stack ventilation effect

To be effective for natural ventilation, the chimney head has to be higher than the roof level, and has to be constructed on the wall facing the sun directly. The suction created at the chimney's base can be used to ventilate and cool the building below. To further maximize the cooling effect, the incoming air may be led through cooler underground ducts before it enters the building.

4.7.2 Air Cooling in Dry Climates

In dry climates, the principle of evaporative cooling can be put to use by passing incoming air over water features, vegetation or underground spaces that tend to humid and cooler. This can lead to cooler air being used for ventilation and have a good natural cooling effect. However, the mechanical energy required to push the air and overcome any pressure drop needs to be considered against the benefits achieved by routing the air for natural air cooling.

4.7.3 Double-Skin Facades

The building façade is sometimes referred to as the skin of the building. A double-skin facade is structured in a way that there is an intermediate cavity in between the two skins where air can flow. The cavity can be ventilated by natural air circulation or through mechanical means. Figure 4.18 shows a photo of a building with double skin façade being assembled in the construction phase. The

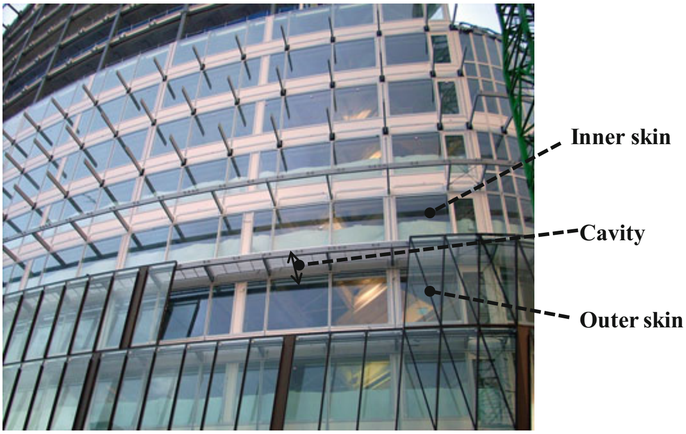


Fig. 4.18 Photo of a building in London showing a double-skin facade being assembled

cavity can be used to vent out hot air to mitigate solar gain in hot climates and that can lead to reduction of cooling load. In cooler climates the solar gain within the cavity can be circulated to the interior space for heating.

4.8 Passive Lighting or Day Lighting

Passive lighting is nothing but using the daylight to illuminate the indoor spaces instead of overly relying on artificial lighting. This can significantly reduce the energy consumption in buildings, especially in spaces that are primarily used or operated in the day time. Daylight or natural light also has several physiological and psychological benefits. It is important however to distinguish daylight from direct sunlight, which can be too intense and result in excessively heating up spaces. What we refer to daylight here is the diffused natural light from the sky that is not too intense and can be used to lit up indoor spaces in buildings. In this section, several techniques to effectively use day lighting are described.

4.8.1 Daylight Apertures or Fenestration

Openings or apertures in the building envelope (referred to as fenestration) can be used to introduce daylighting inside the building. There are different types of fenestration techniques that can used to introduce sufficient daylight in indoor spaces.

Fig. 4.19 Photo showing daylight penetration through glass windows in building space

4.8.1.1 Side Windows

Light coming from the side windows is the most common form of daylighting technique. However, the penetration of such light far into the building indoor spaces is limited. Hence, side windows as primary mode of daylighting work well only with shallow floor plans. Figure 4.19 shows a photo of a room with daylight penetration.

The orientation on side windows is also an important consideration. East or west facing windows are only effective at certain time of the day (i.e. morning or afternoon) and can also cause excessive glare or heating due to direct sunlight. The most even illumination without too much glare or heat can be provided by windows facing away from the sun's path. Other factors such as neighbouring buildings and tall features also need to be taken into account. Hence using side windows for daylighting should be carefully chosen for a particular location considering the sun path, massing and neighbouring developments.

4.8.1.2 Skylight

Skylights are roof based openings that can be effective in bringing light deeper into the building, but can also cause direct sunlight issues in locations near the equator. The majority of commercial and industrial skylights are installed on flat roofs, where the skylight can have an almost unblocked view of the full hemisphere of the sky.

Skylights are available in a wide variety of sizes, shapes and forms (see Fig. 4.20) to match the building and structural requirements. They can range from simple rectangles to pyramids, ridges and other complex polygons. They can also be available in different sizes and be small, to fit between rafters, or large enough to cover the entire length of the building. Figure 4.21 shows photo of a large bubble-shaped skylight installed on spacer frames above an open walkway in a building.

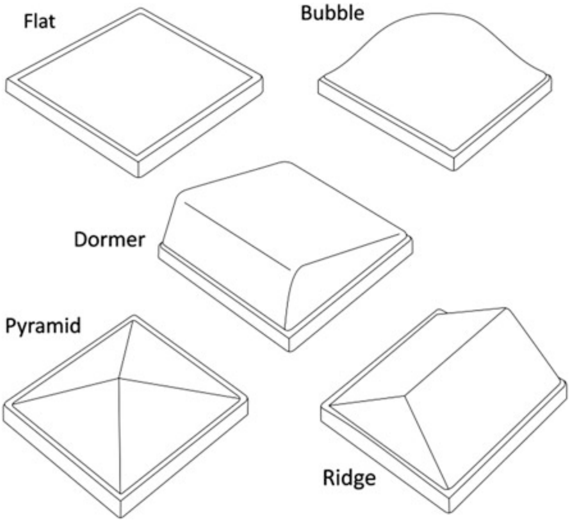


Fig. 4.20 Different basic shapes of skylight

Apart from skylights, there also other kind of apertures to bring light in through roof. As shown in Fig. 4.22, these include clerestory, monitor, and saw-tooth. They differ from each other in how they bring-in the daylight into the space during different seasons and different times of the day.

4.8.2 Light Shelves

Light shelves help light penetration into deep indoor spaces by bouncing visible light up towards the ceiling, which reflect it down deeper into the interior of a room. A light shelf is positioned above eye level and divides a window into a view area on the bottom and a daylighting area on the top (see Fig. 4.23 for illustration of the concept). The light shelf is usually a horizontal element that can be positioned externally, internally, or combined and can either be integral to the building, or mounted upon the building. It can be constructed of materials such as wood, metal, glass, plastic, or fabric. The structural strength, ease of maintenance, cost, and aesthetics of the building are the key considerations for material selection.

External light shelves can double up as shading devices as they can reduce the amount of incoming heat from direct sunlight apart from reflecting light for even distribution. However external light shelves are prone to accumulation of dust and even bird droppings and may require regular cleaning and maintenance. This is where internal light shelves have an advantage. Indoor light shelves however can take up indoor space and are not effective in shading from sunlight.

Fig. 4.21 Photo of a skylight installed above an open walkway in a building

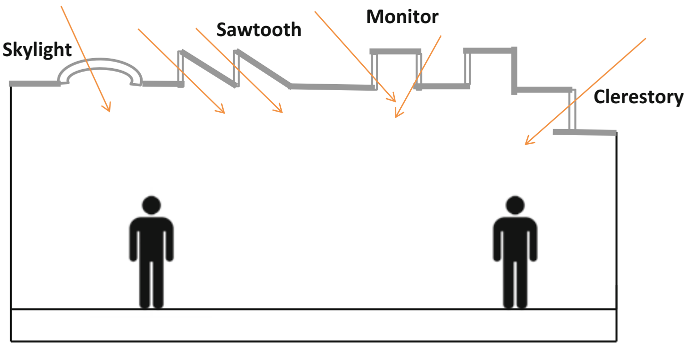


Fig. 4.22 Different types of top (roof-based) lighting techniques

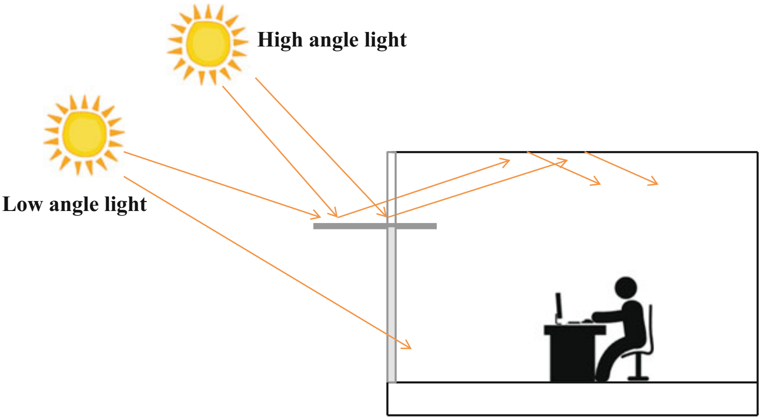


Fig. 4.23 Illustration of the light shelf concept

4.8.3 *Daylight Redirecting Glazing/Window Films*

Although light shelves are an effective method to reflect and bounce light inwards, they are additional architectural elements that require maintenance or take up space. There are now glazing materials or films available that are able to reflect light towards the ceiling and hence can possibly replace light shelves and be more cost-effective.

For example, the 3M Daylight Redirecting Film, utilizes micro-replication to redirect light that would have originally hit the floor a few feet from the window, up onto the ceiling, helping to light the room as deep as 40 feet from the window. The technology “micro-replication” refers to microscopic structures that are able to redirect as much as 80 % of light up onto the ceiling (3M 2016). Apart from 3M, there are other suppliers of daylight redirecting films such as SerraLux Inc. (SerraLux 2016).

Reflectance values from room surfaces will significantly impact daylight performance and should be kept as high as possible. It is desirable to keep ceiling reflectance over 80 %, walls over 50 %, and floors around 20 %. Of the various room surfaces, floor reflectance has the least impact on day lighting penetration (Ander 2014).

4.8.4 Light Pipes and Mirror Ducts

Light tubes or light pipes are physical structures that act as optical wave guides for transporting or distributing light for the purpose of illumination. In their use for daylighting, they are often referred to as sun tubes or sun pipes. They function similar to a skylight, but are designed to optimally introduce light deeper into the building where traditional skylights and windows can't reach. Figure 4.24 shows the illustration of the light pipe concept for indoor lighting.

The light pipe consists of two essential components:

1. A light collection dome that is typically installed similar to skylight, but is hemispherical to bring light in from various angles.
2. A long hollow tube that is attached on one end to the light collection dome and the other end may look like a light fixture that introduces light into the desired space. This tube is typically made up of light reflecting metal and other surfaces that help to reflect and transport light over the length of the tube.

Another variation of the light pipe is a light duct or sometimes called as a mirror duct that consists of a hollow reflective duct to bring daylight deeper into the space.

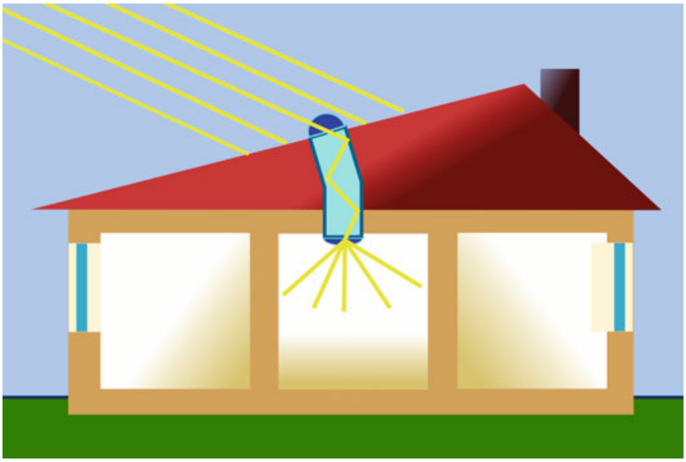


Fig. 4.24 Light pipes for indoor lighting using daylight (Kuhn 2007)

Fig. 4.25 Photo of a mirror duct light collectors installed at a building in Singapore

While sun pipes are mostly installed vertically, mirror ducts are installed horizontally inside a space with light collectors placed outside as shown in the photo in Fig. 4.25.

Mirror ducts are designed to capture daylight through external collectors and the light is channelled into horizontal reflective ducts that are incorporated within the false ceiling. The light then exits through the ceiling apertures or illuminating units into the workspace below. The main advantage of the mirror ducts is that the light it brings into the space is usually glare free.

4.8.5 Transparent Insulation

Transparent insulation differ from traditional building insulation in its ability to transmit daylight through. It typically consist of either glass or plastic material arranged in a honeycomb mesh, capillaries or closed cell construction. Alternatively, granular or monolithic silica aero gel can be used to achieve higher insulation values. The optical and thermal properties can be fine-tunes based on the material selection, its thickness and arrangement. Figure 4.26 shows some examples of transparent insulation materials. Generally transparent insulation is suitable more for cold climates rather than hot climates as it transmits solar radiation through or absorbs it as an thermal mass that can be used for passive heating.

Fig. 4.26 Transparent insulation examples (Happold 2016)

4.8.6 *Measuring Daylight Effectiveness*

In case of day-lighting, the illuminance levels can vary throughout the day depending on the conditions of the sky. A measure of day-lighting effectiveness in a building space is the Daylight Factor (DF). Daylight factors are expressed as the fraction of natural light falling on a work surface compared to that which would have fallen on a completely unobstructed horizontal surface under same sky conditions. The calculation of DF is generally done using standard overcast sky conditions to represent the worst-case scenario for design. The ideal DF for indoor activities is in the range of 2–5 % as anything below that is considered poorly lit and anything more than that can cause implications on thermal comfort. The percentage of working hours when lighting needs are met by day-lighting alone is termed at the Daylight Autonomy (DA).

4.8.7 *Integration with Electric Lighting Controls*

Often times, daylight cannot be fully reliable to achieve continuously uniform illumination for visual comfort. Hence it has to be well controlled and augmented by integration with artificial or electrical lighting systems that will be discussed later in Chap. 5. An integrated control to enable electric light activation on demand can achieve significant energy savings while leveraging on daylight benefits to the maximum. These controls can be configured as follows:

1. Switching controls: on-and-off controls that turn the electric lights off when there is sufficient daylight available.
2. Stepped controls: control individual lamps within an electric luminary system to provide sufficient artificial light to augment the daylight as required.
3. Dimming controls: continuously adjust electric lighting by modulating the power input to lamps to complement the illumination level provided by daylight.

The main element of the daylighting based control is a photo sensor that detects or measures the intensity of daylight and can give appropriate digital signals to the controller for switching or dimming.

References

3M, Daylight redirecting film. Available Online at: http://solutions.3m.com/wps/portal/3M/en_US/Window_Film/Solutions/Markets-Products/Government/Daylight_Redirecting_Film/. Accessed 15 June 2015

Ander GD (2014) Daylighting. Available online at: http://www.wbdg.org/resources/daylighting.php. Accessed 20 Sept 2015

Autodesk (2015) Available online at: http://sustainabilityworkshop.autodesk.com/building-design. Accessed 12 Aug 2015

CRRC (Cool Roof Rating Council) (2015) Available online at: http://coolroofs.org/. Accessed 15 Sept 2015

DOE (Department of Energy) (2015) Energy saver—types of insulation. Available online at: http://energy.gov/energysaver/types-insulation. Accessed 20 Sept 2015

ERI@N (Energy Research Institute at the Nanyang) (2013) Technological University (NTU), Singapore

Happold B (2016) Transparent insulation, updated 22 March 2016. Available online at: http://www.designingbuildings.co.uk/wiki/Transparent_insulation. Accessed 25 Mar 2016

Kuhn S (2007) Wikimedia commons. Available Online at: https://upload.wikimedia.org/wikipedia/commons/thumb/b/bf/Sonnenrohr.svg/1200px-Sonnenrohr.svg.png. Retrieved 12 Nov 2015

Levolux (2012) The cold facts about hot offices, 22 Feb 2012. Available online at: http://levolux.blogspot.sg/2012_02_01_archive.html. Accessed 20 Feb 2016

Magortherm (2015) http://www.magortherm.com/

NFRC (National Fenestration Rating Council) (2012) Available online at: http://www.nfrc.org/WindowRatings/. Accessed: 21 Feb 2016

Penwarden AD, Wise AFE (1975) Wind environment around buildings. BRE report, London

Sefaira (2013) http://sefaira.com/resources/3-ways-to-win-more-bids/

SerraLux (2016) http://serraluxinc.com/serraglaze-daylight-redirecting-film/serraglaze-behavior/

Urban B, Roth K (2010) Guidelines for selecting cool roofs. U.S. Department of Energy. Available online at: https://heatisland.lbl.gov/sites/all/files/coolroofguide_0.pdf. Retrieved 3 Nov 2015