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An Overview of Passive Cooling Techniques in Buildings: Design Concepts and Architectural Interventions

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Abstract

There has been a drastic increase in the use of air conditioning system for cooling the buildings all around the world. The last two decade has witnessed a severe energy crisis in developing countries especially during summer season primarily due to cooling load requirements of buildings. Increasing consumption of energy has led to environmental pollution resulting in global warming and ozone layer depletion. Passive cooling systems use non-mechanical methods to maintain a comfortable indoor temperature and are a key factor in mitigating the impact of buildings on the environment. Passive cooling techniques can reduce the peak cooling load in buildings, thus reducing the size of the air conditioning equipment and the period for which it is generally required. This paper reviews and critically analyzes various passive cooling techniques and their role in providing thermal comfort and its significance in energy conservation.

Keywords: Natural Cooling, Passive cooling, Techniques, climatic design, energy conservation.

1. Introduction

The last two decade has witnessed a severe energy crisis in developing countries especially during summer season primarily due to cooling load requirements of buildings. The energy consumption in buildings is quite high and is expected to further increase because of improving standards of life and increasing world population. Air conditioning use has increasingly penetrated the market during the last few years and greatly contributes in the upsurge of absolute energy consumption.

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According to the World watch Institute, buildings consume about 40% of the world's energy production. As a result, buildings are involved in producing about 40% of the sulfur dioxide and nitrogen oxides that cause acid rain and contribute to smog formation. Building energy use also produces 33% of all annual carbon dioxide emissions, significantly contributing to the climate changes brought about by the accumulation of this heat-trapping gas [1]. In India, the building sector represents about 33% of total electricity consumption, with commercial sector accounting for 8% and 25 % respectively [2].

Before the advent of mechanical refrigeration, ingenious use was made of the many means of cooling (e.g. damp cloths hung in draughts created by the connective stack effect in buildings). So dwellings and life styles were developed to make best possible use of these sources of cooling. The introduction of mechanical refrigeration permitted not only the ability to increase the likelihood of achieving complete thermal comfort for more extended periods, but also a great deal of flexibility in building design, and simultaneously led to changes in life style and work habits. However, increasingly, the use of a 'higher technology' resulted in natural-cooling techniques being ignored. Now with the growing realization of the rapid depletion of non-renewable energy sources and of the adverse environmental impacts of fossil-fuel dissipating processes, it is accepted that it is foolish to continue consuming vast amounts of non-renewable fuels for the air-conditioning of buildings, when our ancestors achieved thermal comfort by natural means [3]. Hence to reduce the emission of greenhouse gases, caused by fossil fuels to power the cooling requirement of the buildings has stimulated the interest towards adoption of passive cooling techniques for buildings. This paper reviews and discusses in detail various passive cooling techniques with a special focus on solar shading techniques, as they are most economical and thus most suitable for houses in developing countries.

2. Passive cooling of buildings

A 'passive' solar design involves the use of natural processes for heating or cooling to achieve balanced interior conditions. The flow of energy in passive design is by natural means: radiation, conduction, or convection without using any electrical device. Maintaining a comfortable environment within a building in a hot climate relies on reducing the rate of heat gains into the building and encouraging the removal of excess heat from the building. To prevent heat from entering into the building or to remove once it has entered is the underlying principle for accomplishing cooling in passive cooling concepts. This depends on two conditions: the availability of a heat sink which is at a lower temperature than indoor air, and the promotion of heat transfer towards the sink. Environmental heat sinks are:

- Outdoor air (heat transfer mainly by convection through openings)
- Water (heat transfer by evaporation inside and / or outside the building envelope)
- The (night) sky (heat transfer by long wave radiation through the roof and/or other surface adjacent to a building
- Ground (heat transfer by conduction through the building envelope)

Passive cooling techniques can reduce the peak cooling load in buildings, thus reducing the size of the air conditioning equipment and the period for which it is generally required. The important cooling concepts like shading are discussed in details:

2.1 Solar shading

Among all other solar passive cooling techniques solar shading is relevant to thermal cooling of buildings especially in a developing country owing to their cost effectiveness and easy to implement. Rural India and developing countries in Middle-east region has witnessed a steep rise masonry houses with RCC roofs. However the availability of electric power in the villages especially during summer is limited. These RCC roofs tend to make the indoor temperature very high around 41°C: This is due to high roof top temperature of around 65°C in arid regions. Solar shading with locally available materials like terracotta tiles, hay, inverted earthen pots, date palm branches etc. can reduce this temperature significantly.

Shading with tree reduces ambient temperature near outer wall by 2°C to 2.5°C. On an average a depression of six degree centigrade in room temperature has been observed when solar shading techniques are adopted [4]. Kumar, Garg and Kaushik evaluated the performance of solar passive cooling techniques such as solar shading, insulation of building components and air exchange rate. In their study they found that a decrease in the indoor temperature by about 2.5°C to 4.5°C is noticed for solar shading. Results modified with insulation and controlled air exchange rate showed a further decrease of 4.4°C to 6.8°C in room temperature. The analysis suggested that solar shading is quite useful to development of passive cooling system to maintain indoor room air temperature lower than the conventional building without shade [5].

2.1.1 Shading by overhangs, louvers and awnings etc.

Well-designed sun control and shading devices, either as parts of a building or separately placed from a building facade, can dramatically reduce building peak heat gain and cooling requirements and improve the natural lighting quality of building interiors. The design of effective shading devices will depend on the solar orientation of a particular building facade. For example, simple fixed overhangs are very effective at shading south-facing windows in the summer when sun angles are high.

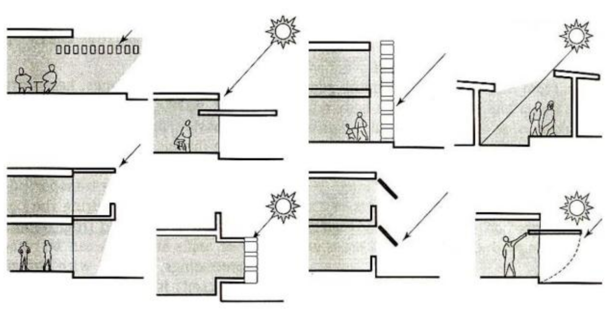


Figure 1. Different types of shading devices.

However, the same horizontal device is ineffective at blocking low afternoon sun from entering west-facing windows during peak heat gain periods in the summer. Fig. 1 shows the different types of shading devices.

2.1.2 Shading of roof

Shading the roof is a very important method of reducing heat gain. Roofs can be shaded by providing roof cover of concrete or plants or canvas or earthen pots etc. Shading provided by external means should not interfere with night-time cooling. A cover over the roof, made of concrete or galvanized iron sheets, provides protection from direct radiation. Disadvantage of this system is that it does not permit escaping of heat to the sky at night-time (Fig. 2).

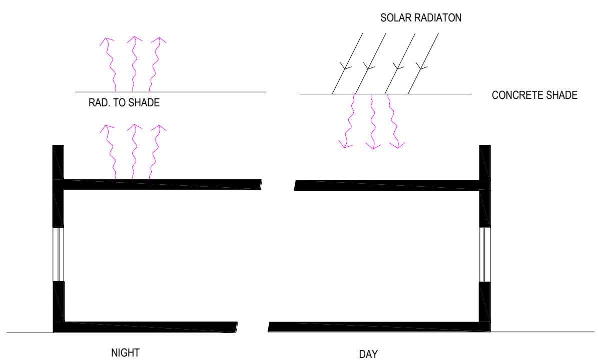


Figure 2. Roof shading by solid cover.

A cover of deciduous plants and creepers is a better alternative. Evaporation from the leaf surfaces brings down the temperature of the roof to a level than that of the daytime air temperature. At night, it is even lower than the sky temperature (Fig. 3).

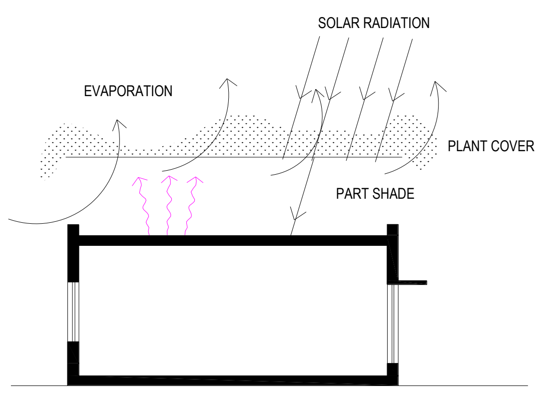


Figure 3. Roof shading by plant cover.

Covering of the entire surface area with the closely packed inverted earthen pots, as was being done in traditional buildings, increases the surface area for radiative emission. Insulating cover over the roof impedes heat flow into the building. However, it renders the roof unusable and maintenance difficult (Fig. 4). Broken china mosaic or ceramic tiles can also be used as top most layer in roof for reflection of incident radiation.

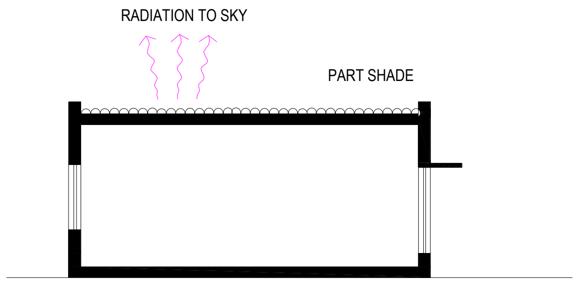


Figure 4. Roof shading by earthen pots.

Another inexpensive and effective device is a removable canvas cover mounted close to the roof. During daytime it prevents entry of heat and its removal at night, radiative cooling. Fig. 5 shows the working principle of removable roof shades. Painting of the canvas white minimizes the radiative and conductive heat gain [6].

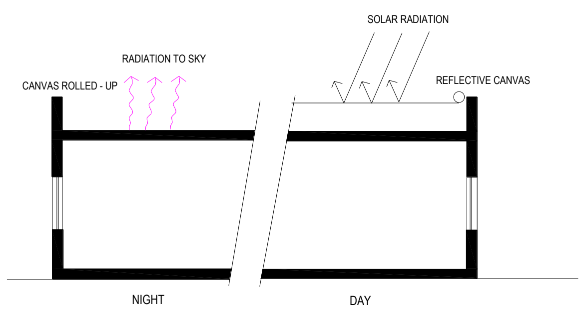


Figure 5. Removable roof shades.

2.1.3 Shading by trees and vegetation

Proper Landscaping can be one of the important factors for energy conservation in buildings. Vegetation and trees in particular, very effectively shade and reduce heat gain. Trees can be used with advantage to shade roof, walls and windows. Shading and evapotranspiration (the process by which a plant actively release water vapor) from trees can reduce surrounding air temperatures as much as 5°C. Different types of plants (trees, shrubs, vines) can be selected on the basis of their growth habit (tall, low, dense, light permeable) to provide the desired degree of shading for various window orientations and situations. The following points should be considered for summer shading [7]:

1. Deciduous trees and shrubs provide summer shade yet allow winter access. The best locations for deciduous trees are on the south and southwest side of the building. When these trees drop their leaves in the winter, sunlight can reach inside to heat the interiors.

2. Trees with heavy foliage are very effective in obstructing the sun's rays and casting a dense shadow. Dense shade is cooler than filtered sunlight. High branching canopy trees can be used to shade the roof, walls and windows.

3. Evergreen trees on the south and west sides afford the best protection from the setting summer sun and cold winter winds.

4. Vertical shading is best for east and west walls and windows in summer, to protect from intense sun at low angles, e.g. screening by dense shrubs, trees, deciduous vines supported on a frame, shrubs used in combination with trees.

5. Shading and insulation for walls can be provided by plants that adhere to the wall, such as English ivy, or by plants supported by the wall, such as jasmine.

6. Horizontal shading is best for south-facing windows, e.g. deciduous vines (which lose foliage in the winter) such as ornamental grape or wisteria can be grown over a pergola for summer shading.

2.1.4 Shading by textured surfaces

Surface shading can be provided as an integral part of the building element also. Highly textured walls have a portion of their surface in shade as shown in Figure 5. The increased surface area of such a wall results in an increased outer surface coefficient, which permits the sunlit surface to stay cooler as well as to cool down faster at night (Fig. 6).

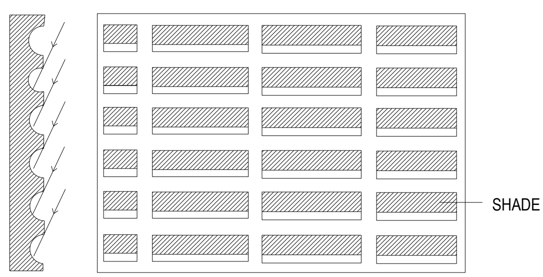


Figure 6. Shading due to surface texture

2.2 Insulation

The effect of insulation is to reduce heat gain and heat loss. The more insulation in a building exterior envelope, the less heat transferred into or out of the building due to temperature difference between the interior and exterior. Insulation also controls the interior mean radiant temperature (MRT) by isolating the interior surfaces from the influence of the exterior conditions, and also reduces draughts produced by temperature differences between walls and air. Insulation is of great value when a building requires mechanical heating or cooling and helps reduce the space-conditioning loads. Location of insulation and its optimum thickness are very important. In hot climates, insulation is placed on the outer face (facing exterior) of the wall or roof so that thermal mass of the wall is weakly coupled with the external source and strongly coupled with the interior. Use of 40 mm thick expanded polystyrene insulation on walls and vermiculite concrete insulation on the roof has brought down space-conditioning loads of the RETREAT building in Gurgaon by about 15% [8]. Air cavities within walls or an attic space in the roof ceiling combination reduce the solar heat gain factor, thereby reducing space-conditioning loads. The performance improves if the void is ventilated. Heat is transmitted through the air cavity by convection and radiation.

2.3 Induced ventilation techniques

2.3.1 Solar chimney

A solar chimney is a modern device that induces natural ventilation by the thermal-buoyancy effect. The structure of the chimney absorbs solar energy during the day, thereby heating the enclosed air within and causing it to rise. Thus air is drawn from the building into an open near the bottom of the chimney. The air exhausted from the house, through the chimney, is replaced by ambient air. However, if the latter is warmer than the air inside the house, as it usually is during the day in hot climates, the continued use of the solar chimney will then begin to heat the structure of the building previously cooled overnight [9]. The solar chimney is used to exhaust hot air from the building at a quick rate, thus improving the cooling potential of incoming air from other openings. Thus solar chimneys having a relatively low construction cost, can move air without the need for the expenditure of conventional forms of energy, and can help achieve comfort by cooling the building structure at night. They can also improve the comfort of the inhabitants during the day if they are combined with an evaporative-cooling device.

2.3.2 Air vents

Curved roofs and air vents are used in combination for passive cooling of air in hot and dry climates, where dusty winds make wind towers impracticable. Suited for single units, they work well in hot and dry and warm and humid climates. A hole in the apex of the domed or cylindrical roof with the protective cap over the vent directs the wind across it (Fig. 7). The opening at the top provides ventilation and provides an escape path for hot air collected at top. Arrangements may be made to draw air from the coolest part of the structure as replacement, to set up a continuous circulation and cool the living spaces. The system works on the principle of cooling by induced ventilation, caused by pressure differences.

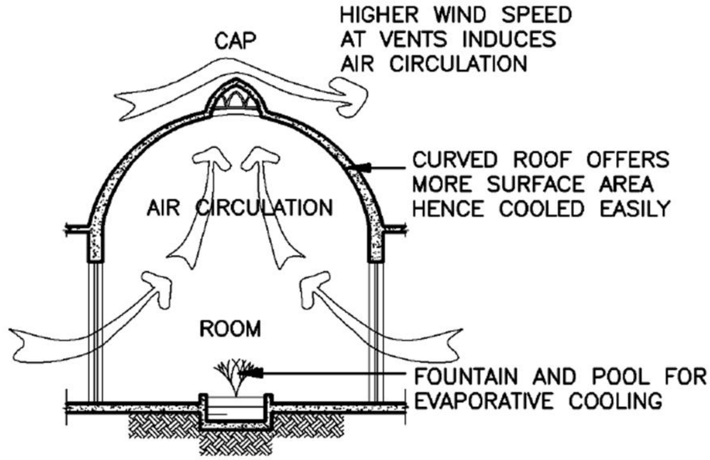


Figure 7. Induced ventilation through curved roof and air vents

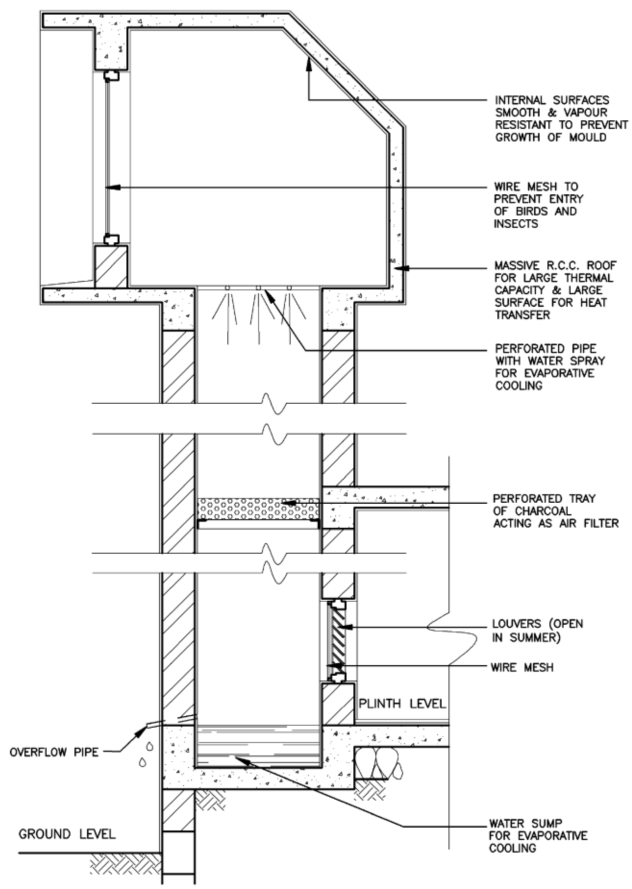


Figure 8. Section showing detail of a wind tower.

2.3.4 Wind tower

In a wind tower, the hot ambient air enters the tower through the openings in the tower, gets cooled, and thus becomes heavier and sinks down. The inlet and outlet of rooms induce cool air movement. When an inlet is provided to the rooms with an outlet on the other side, there is a draft of cool air. It resembles a chimney, with one end in the basement or lower floor and the other on the roof. The top part is divided into several vertical air spaces ending in the openings in the sides of the tower (Fig. 8). In the presence of wind, air is cooled more effectively and flows faster down the tower and into the living area. The system works effectively in hot and dry climates where diurnal variations are high. Figure 8 shows the section and detail of a wind tower.

2.4 Radiative cooling

The roof of a building can be used both as a nocturnal radiator and also as a cold store. It is often a cost-effective solution. During the night the roof is exposed to the night sky, losing heat by long-wave radiation and also by convection. During the day, the roof is externally insulated in order to minimize the heat gains from solar radiation and the ambient air. The roof then absorbs the heat from the room below.

2.4.1 Diode roof

The diode roof eliminates the water loss by evaporation and reduces heat gains without the need for movable insulation. It is a pipe system, consisting of a corrugated sheet-metal roof on which are placed polyethylene bags coated with white titanium oxide each containing a layer of pebbles wetted with water. The roof loses heat by long-wave heat radiation to the sky and by the evaporation of water which condenses on the inside surface of the bags and drops back onto the pebbles. By this means, it is possible to cool the roof to 4°C below the minimum air temperature [10].

2.4.2 Roof pond

In this system a shallow water pond is provided over highly conductive flat roof with fixed side thermal insulation. The top thermal insulation is movable. The pond is covered in day hours to prevent heating of pond from solar radiation. The use of roof pond can lower room temperature by about 20°C. While keeping the pond open during night the water is cooled by nocturnal cooling. The covered pond during the day provides cooling due to the effect of nocturnally cooled water pond and on other side the thermal insulation cuts off the solar radiation from the roof. The system can be used for heating during the winter by operating the system just reverse. The movable insulation is taken away during day so the water of pond gets heated up by solar radiation and heating the building. The pond is covered in night to reduce the thermal losses from the roof and the hot water in the pond transfers heat into building [11].

2.5 Evaporative cooling

Evaporative cooling is a passive cooling technique in which outdoor air is cooled by evaporating water before it is introduced in the building. Its physical principle lies in the fact that the heat of air is used to evaporate water, thus cooling the air, which in turn cools the living space in the building. However passive evaporative cooling can also be indirect. The roof can be cooled with a pond, wetted pads or spray, and the ceiling transformed into a cooling element that cools the space below by convection and radiation without raising the indoor humidity.

2.5.1 Passive downdraft evaporative cooling (PDEC)

Passive downdraft evaporative cooling systems consist of a downdraft tower with wetted cellulose pads at the top of the tower. Water is distributed on the top of the pads, collected at the bottom into a sump and re-circulated by a pump. Certain designs exclude the re-circulation pump and use the pressure in the supply water line to periodically surge water over the pads, eliminating the requirement for any electrical energy input. In some designs, water is sprayed using micronisers or nozzles in place of pads, in others, water is made to drip. Thus, the towers are equipped with evaporative cooling devices at the top to provide cool air by gravity flow. These towers are often described as reverse chimneys. While the column of warm air rises in a chimney, in this case the column of cool air falls. The air flow rate depends on the efficiency of the evaporative cooling device, tower height and cross section, as well as the resistance to air flow in the cooling device, tower and structure (if any) into which it discharges [12]. Passive downdraft evaporative cooling tower has been used successfully at the Torrent Research Centre in Ahmedabad (Fig. 9). The inside temperatures of 29 –30 °C were recorded when the outside temperatures were 43 – 44 °C. Six to nine air changes per hour were achieved on different floors.

Figure 9. Passive Downdraught Evaporative Cooling in Torrent Research Centre, Ahmedabad.

2.5.2 Roof surface evaporative cooling (RSEC)

In a tropical country like India, the solar radiation incident on roofs is very high in summer, leading to overheating of rooms below them. Roof surfaces can be effectively and inexpensively cooled by spraying water over suitable water-retentive materials (e.g., gunny bags) spread over the roof surface. Wetted roof surface provides the evaporation from the roof due to unsaturated ambient air. As the water evaporates, it draws most of the required latent heat from the surface, thus lowering its temperature of the roof and hence reduces heat gain. Therefore, the wetted roof temperatures 40°C are much lower than the ambient air about 55°C. However, the water requirement for such arrangement is very high and it is a main constrain in the arid region to adopt this technique [11].

2.6 Earth coupling

This technique is used for passive cooling as well as heating of buildings, which is made possible by the earth acting as a massive heat sink. At depths beyond 4 to 5m, both daily and seasonal fluctuations die out and the soil temperature remains almost constant throughout the year. Thus, the underground or partially sunk buildings will provide both cooling (in summer) and heating (in winter) to the living space. A building may be coupled with the earth by burying it underground or berming. Figure 9 shows the functioning of earth berming during summer and winter [13].

2.6.1 Earth air tunnel

The use of earth as a heat sink or a source for cooling/heating air in buried pipes or underground tunnels has been a testimony to Islamic and Persian architecture. The air passing through a tunnel or a buried pipe at a depth of few meters gets cooled in summers and heated in winters (Fig. 10). Parameters like surface area of pipe, length and depth of the tunnel below ground, dampness of the earth, humidity of inlet air velocity, affect the exchange of heat between air and the surrounding soil.

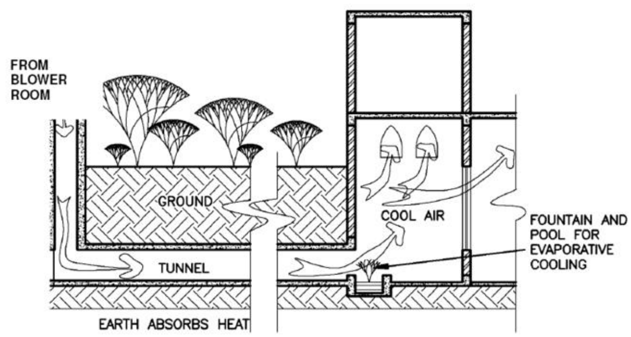
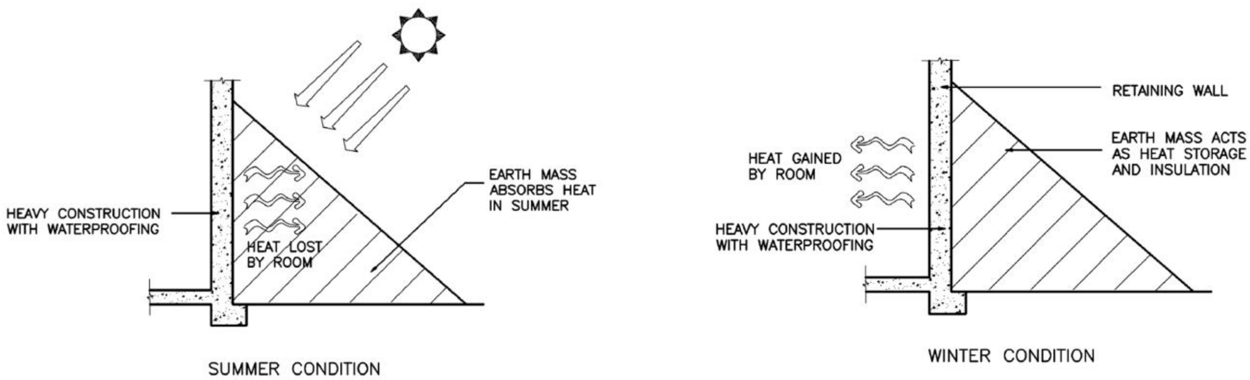


Figure 10. Working principle of earth air tunnel.

2.6.2 Earth berming

In an earth sheltered building or earth bermed structure the reduced infiltration of outside air and the additional thermal resistance of the surrounding earth considerably reduces the average thermal load. Further the addition of earth mass of the building acts like a large thermal mass and reduces the fluctuations in the thermal load. Besides reducing solar and convective heat gains, such buildings can also utilize the cooler sub-surface ground as a heat sink. Hence with reference to thermal comfort, an earth sheltered building presents a significant passive approach. Fig. 11(a) and Fig. 11(b) shows the working principle of earth berming during summer and winter conditions.



(a) (b)

Figure 11. Working principle of earth berming during summer (a) and winter (b) conditions.

2.7 Desiccant cooling

Desiccant cooling is effective in warm and humid climates. Natural cooling of human body through sweating does not occur in highly humid conditions. Therefore, a person’s tolerance to high temperature is reduced and it becomes desirable to decrease the humidity level. In the desiccant cooling method, desiccant salts or mechanical dehumidifiers are used to reduce humidity in the atmosphere. Materials having high affinity for water are used for dehumidification. They can be solid like silica gel, alumina gel and activated alumina, or liquids like triethylene glycol. Air from the outside enters the unit containing desiccants and is dried adiabatically before entering the living space. The desiccants are regenerated by solar energy. Sometimes, desiccant cooling is employed in conjunction with evaporative cooling, which adjusts the temperature of air to the required comfort level [13].

3. Conclusion

In this paper several passive cooling techniques were reviewed and discussed with reference to their design implications and architectural interventions. The continuing increase of energy consumption of air conditioning suggests a more profound examination of the urban environment and the impact on buildings as well as to an extended application of passive cooling techniques. Appropriate research should aim at better understanding micro-climates around buildings, and to understand and describe comfort requirements under transient conditions during the summer period. Also of importance are improving quality aspects, developing advanced passive and hybrid cooling systems, and finally, developing advanced materials for the building envelope [14].

Theoretical studies have shown that the application of all the above techniques in buildings may decrease their cooling load up to 50% - 70%. Generally, concern for energy consumption is only marginal in the majority of architectural-design practices, even in the developed countries. Passive solar energy-efficient building design should be the first aim of any building designer, because, in most cases, it is a relatively low-cost exercise that will lead to savings in the capital and operating costs of the air-conditioning plant. In today's architecture, it is now essential for architects and building engineers to incorporate passive cooling techniques in buildings as an inherent part of design and architectural expression and they should be included conceptually from the outset. Incorporation of these passive cooling techniques would certainly reduce our dependency on artificial means for thermal comfort and minimize the environmental problems due to excessive consumption of energy and other natural resources and hence will evolve a built form, which will be more climate responsive, more sustainable and more environmental friendly of tomorrow.

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