

# Passive cooling methods for energy efficient buildings with and without thermal energy storage – A review

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**Abstract**

This paper reviews the various possible methods of passive cooling for buildings and discusses the representative applications of each method. Passive cooling techniques are closely linked to the thermal comfort of the occupants, and it is possible to achieve this comfort by reducing the heat gains, thermal moderation and removing the internal heat. In the present review the various methods adopted under these techniques and the relevant information about the performance of each method reported by various researchers, are collected and presented in detail.

*Keywords:* Energy efficient buildings; Solar control; Passive cooling; Natural ventilation; Thermal storage; Free cooling; Phase change materials

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**1. Introduction**

Cooling is the transfer of energy from a space or from the air, to a space, in order to achieve a lower temperature than that of the natural surroundings. In recent years, air conditioning systems are used to control the temperature, moisture content, circulation and purity of the air within a space, in order to achieve the desired effects for the occupants. The shortage of conventional energy sources and escalating energy costs have caused the re-examination of the general design practices and applications of air conditioning systems and the development of new technologies and processes for achieving comfort conditions in buildings by natural means.

In recent years, the rapid economical growth in some of the thickly populated nations has stimulated the utilization of sustainable energy sources and energy conservation methodologies considering environmental protection. Globally, buildings are responsible for approximately 40% of the entire world's annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling and air-conditioning. The increasing level of damage to the environment has created greater awareness at the international level, which resulted in the concept of green energy building in the infrastructural sector. Hence, the major focus of researchers, policy makers, environmentalists and building architects has been on the conservation of energy and its utilization in buildings. It is further established that alternative energy sources, techniques and systems can be used to satisfy a major portion of the cooling needs in buildings.

This topic, natural and passive cooling, covers all natural processes and techniques for cooling buildings. It is cooling without any form of energy input, other than renewable energy sources. Passive cooling techniques are also closely linked to the thermal comfort of the occupants. It is also possible to increase the effectiveness of passive cooling with mechanically assisted heat transfer techniques, which enhance the natural cooling processes discussed by [1]. Such applications are called "hybrid" cooling systems. Energy consumption is maintained at very low levels, but the efficiency of the systems and their applicability is greatly improved.

The passive cooling of buildings is broadly categorized under three sections (i). Heat prevention/reduction, (Reduce heat gains) (ii). Thermal moderation (Modify heat gains) and (iii). Heat Dissipation (Remove internal heat). The various methods adopted for each of these, are further classified and given in Fig. 1.

In the present work a detailed review has been made on the various techniques adopted to achieve thermal comfort in buildings under the above said 3 sections.

## **2. Solar and heat protection techniques (*Reduce heat gains*)**

A building must be adapted to the climate of the region and its microclimate. It is very important to minimize the internal gains of a building in order to improve the effectiveness of passive cooling techniques. The site design is influenced by economic considerations, zoning regulations and adjacent developments, all of which can interfere with the design of a building, with regard to the incident solar radiation and the available wind. Vegetation can not only result in pleasant outdoor spaces, but can also improve the microclimate around a building and reduce the cooling load. Solar control is the primary design measure for heat gain protection. The use of various shading devices to prevent the attenuation of the incident solar radiation from entering into the building is discussed by [2].

### *2. 1. Microclimate*

Climate is the average of the atmospheric conditions over an extended time over a large region. Small-scale patterns of climate, resulting from the influence of topography, soil structure, ground and urban forms, are known as microclimates. The principal parameters characterizing climate are air temperature, humidity, precipitation and wind.

The climate of cities differs from the climate of the surrounding rural areas, due mainly to the structure of cities and the heat released by vehicles. In general, the climate in cities is characterized by ambient temperatures, reduced relative humidity, reduced wind speed and reduced received direct solar radiation.

The microclimate of an urban area can be modified by appropriate landscaping techniques, with the use of vegetation and water surfaces, and can be applied to public places, such as parks, play-grounds and streets [3].

The first stage in managing higher future internal temperatures in buildings is to attempt to make the external air as cool as possible. Within the built environment this involves enhancing the green and blue infrastructure of parks, trees, open spaces, open water and water features. There is a growing interest in the use of rooftop gardens, green walls and green roofs for their cooling effect [4]. Parks and other open green spaces can be beneficial through their cooling effects in summer, through shading and transpiration [5-7], and improved access for natural wind-driven ventilation. In addition, the presence of water, plants and trees contributes to microclimate cooling, and is an important source of moisture within the mostly arid urban environment [8]. Urban surfaces should be cool or reflective to limit solar gain. Pavements, car parks and roads can be constructed with lighter finishes and have more porous structures.

Limor Shashua-Bar et al. [9] studied the climatic analysis of landscape strategies for outdoor cooling in a hot-arid region, considering the efficiency of water use. Six landscape strategies were studied, using different combinations of trees, lawn, and an overhead shade mesh.

#### *2. 1. 1. Vegetation*

Vegetation modifies the microclimate and the energy use of buildings by lowering the air and surface temperatures and increasing the relative humidity of the air. Furthermore, plants can control air pollution, filter the dust and reduce the level of nuisance from noise sources.

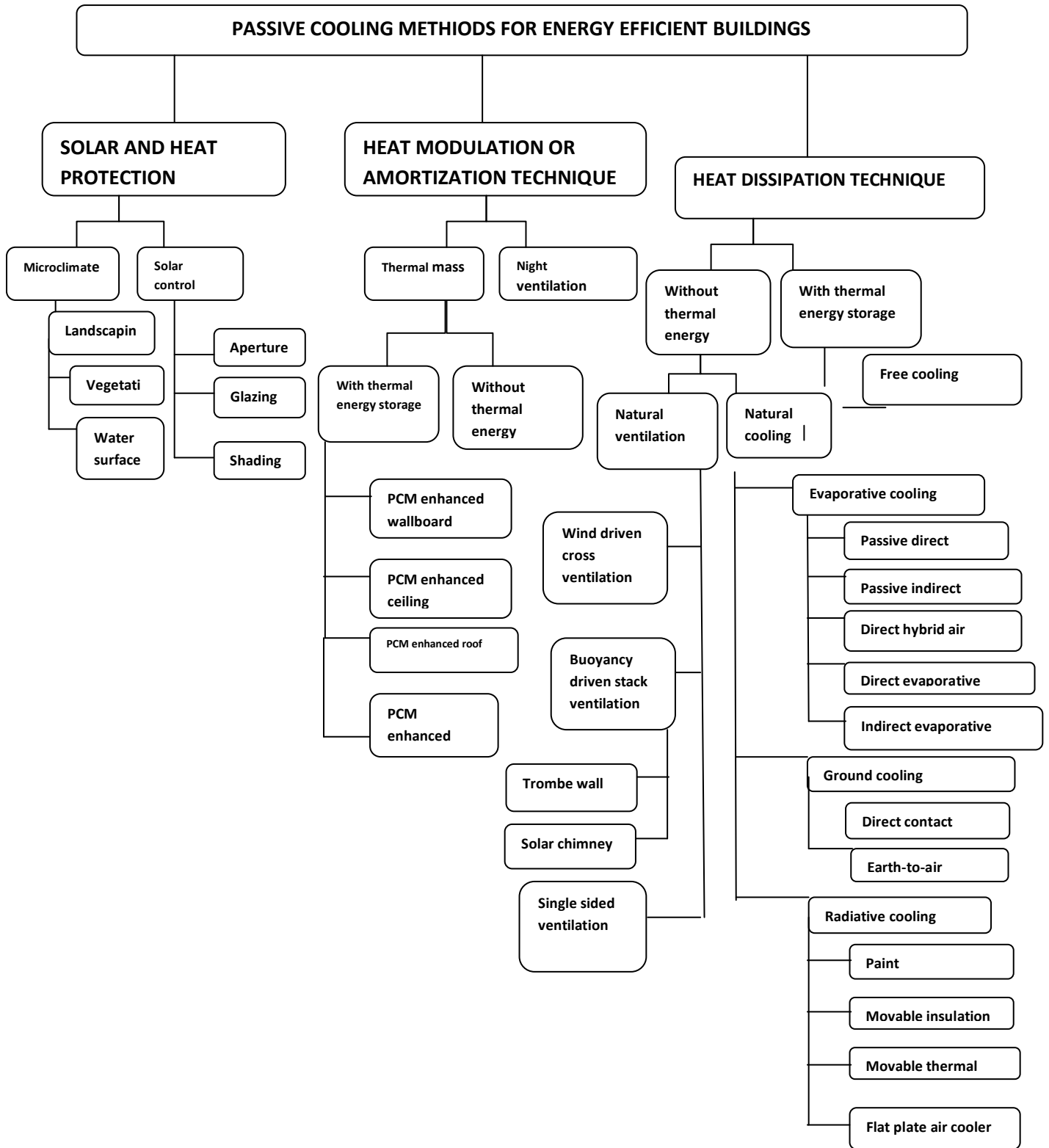


Fig. 1. Classification of passive cooling methods in energy efficient buildings.

Indoor simulations still tend to be isolated from an important element affecting urban microclimate, such as urban trees. The main advantage of urban trees, as a bioclimatic responsive design element is to produce shade, whereas its main disadvantage is blocking the wind [10]. In addition the effects of specific urban tree types - for example, the different leaf area densities and evapotranspiration rates of urban trees influence solar access and heat exchanges if planted around buildings [11].

Eumorfopoulou and Kontoleon and Kontoleon and Eumorfopoulou [12, 13] analyzed thoroughly the influence of the orientation and proportion (covering percentage) of plant-covered wall sections on the thermal behavior of typical buildings in Greece during the summer.

Limor Shashua-Bar et al. [14] have analyzed the thermal effect on an urban street due to three levels of building densities. The study indicated the importance of urban trees in alleviating the heat island effect in a hot and humid summer. In all the studied cases, the thermal effect of the tree was found to depend mainly on its canopy coverage level and planting density in the urban street, and a little on other species characteristics.

### *2. 1. 2. Water surfaces*

Water surfaces modify the microclimate of the surrounding area, reducing the ambient air temperature, either by evaporation, or by the contact of the hot air with the cooler water surface. Fountains, ponds, streams, waterfalls or mist sprays may be used as cooling sources, for lowering the temperature of the outdoor air and of the air entering the building.

The asphalt and concrete used in urban environments is typically too dense to allow water permeability, and therefore, drastically limits the latent heat exchange. The water and air passage allows latent heat exchange, and therefore decreases the temperature of the pavement. This, in turn, assists trees and other landscape root systems to better access air and nutrients, providing cooler root zones which result in larger and denser shading landscape materials [15].

### *2. 2. Solar control*

Solar radiation reaches the external surfaces of a building in direct, diffuse and reflected forms and penetrates to the interior through transparent elements. In general, incident radiation varies with geographic latitude, the altitude above sea level, the general atmospheric conditions, the day of the year, and the time of the day. For a given surface, incident radiation varies with the orientation and the surface's angle to the horizontal plane.

The admission of solar radiation into an interior space may cause problems, such as high indoor temperatures, thermal and visual discomfort to the occupants, damage to sensitive objects and furnishings. Thus, it is of vital importance that solar radiation should be controlled. Solar control denotes the complete or partial, permanent or temporary exclusion of solar radiation from building surfaces or interior or surrounding spaces. Solar control may be achieved through the following techniques.

#### *2. 2. 1. Aperture*

The appropriate combination of the orientation, size and tilt of the various openings on the building's envelope is of vital importance. This is because these parameters affect the surface's

view of the sun and sky over the daily and monthly cycles. Mazria [16] defines the best orientation for the solar apertures of a building as one which receives the maximum amount of solar radiation in winter and the minimum amount in summer. Designing the building form from the perspective of energy efficiency means considering the floor area, perimeter, building height and aspect ratio. A study, gave out an aspect ratio of 1:1.25 for Ankara [17] and this value is accepted for buildings with a 100 m<sup>2</sup> floor area.

### 2. 2. 2. *Glazing*

The thermal properties of the glazed surfaces of a building affect the penetration of solar radiation to the interior. The influences of channel width and the dimensions of the inlet and outlet openings affect the convection process, and hence, affect the overall heating performance. Using double glazing could increase the flow rate by 11-17%. On the other hand, insulating the interior surface of the storage wall for summer cooling can avoid excessive overheating due to south facing glazing [18].

Research in the field of glazing system technology received a boost, passing from a single pane to low-emittance window systems, and again to low thermal transmittance, vacuum glazings, electrochromic windows, thermotropic materials, silica aerogels and transparent insulation materials (TIM) [19-21].

Transparent selective films represent an interesting option for the control of solar heat gain, to be used to treat windows or façades, especially in existing buildings, to improve the performance of windows and transparent façades. Transparent selective coatings and films are being manufactured nowadays by all major glass and glazing companies all over the world. They represent quite an advanced technology and are being increasingly used in double and even triple glazing systems to improve window performance.

Many researchers have investigated the optical properties of selective coatings and films for window applications. Roos et al. [22] investigated the effect of the angle of incidence of solar radiation on the optical properties of solar control windows. Nostell [23] presented the results of a wide experimental campaign on various coatings, while Durrani et al. [24] measured the optical properties of three-layer systems on glass substrates. The modelling of complex fenestration systems (CFS), including multi-layer glass panes, solar control films, translucent materials and shading devices, has been done by various researchers. Alvarez et al. [25] modelled the heat transfer of multiple-layer glazing with selective coatings, while Li et al. [26] evaluated the benefits with regard to lighting and cooling energy consumption in an office building using solar control films. Maestre et al. [27] developed a new model for the angle dependent optical properties of coated glazing, while Laouadi and Parekh. [28, 29] developed optical models of complex fenestration systems based on the bidirectional optical property distribution functions. A recent study, Bakker and Visser [30] demonstrated that a larger use of solar control glazing in residential buildings in European Union countries could avoid the emission of up to 80 million tons of CO<sub>2</sub>, which represents 25% of the target established by the European Commission for energy savings in the residential sector in 2020. Gijón-Rivera et al. [31] made an assessment of the thermal performance of an office on the top of a building with four different configurations of window glass, and their influence on the indoor conditions. NohPat et al. [32] observed that the use of solar control film in their numerical analysis observed that the double glazing unit is highly recommended due to energy gain reduction by 55% compared to the traditional DGU without solar control film.

Ruben Baetens et al. [33] made a survey on the prototype and the currently commercial dynamic tintable smart windows, and concluded that the commercial electrochromic windows seem most promising to reduce cooling loads, heating loads and lighting energy in buildings, where they have been found most reliable, and able to modulate the transmittance of up to 68% of the total solar spectrum.

### 2. 2. 3. *Insulation*

Belusko et al. [34] investigated the thermal resistance for the heat flow through a typical timber framed pitched roofing system measured under outdoor conditions for heat flow up. However, with higher thermal resistance systems containing bulk insulation within the timber frame, the measured result for a typical installation was as low as 50% of the thermal resistance determined considering two dimensional thermal bridging using the parallel path method. This result was attributed to three dimensional heat flow and insulation installation defects, resulting from the design and construction method used. Translating these results to a typical house with a 200 m<sup>2</sup> floor area, the overall thermal resistance of the roof was at least 23% lower than the overall calculated thermal resistance including two dimensional thermal bridging.

Ong [35] reported that the heat transmission through the roof could be reduced by providing insulation in the attic under the roof or above the ceiling. A roof solar collector could provide both ventilation and cooling in the attic. Several laboratory sized units of passive roof designs were constructed and tested side-by-side under outdoor conditions to obtain temperature data of the roof, attic and ceiling in order to compare their performances.

### 2. 2. 4. *Shading*

Shading denotes the partial or complete obstruction of the sunbeam directed toward a surface by an intervening object or surface. The shadow varies in position and size depending upon the geometric relationship between the sun and the surface concerned.

Shading devices are essentially a second link between daylighting and the thermal performance of perimeter spaces. Thus, an integrated analysis should be carried out in order to take into account the interactions between the different parameters and to attain optimal results. However, with a few exceptions, an integrated façade analysis is not applied at the early design stage, when critical decisions with small economic impact could lead to significant energy savings during the lifetime of the building, and a simultaneous improvement in interior conditions [36]. Li et al. [37] studied the effect of daylighting and energy use in heavily obstructed residential buildings in Honk Kong. They simulated the daylighting performance of high rise buildings by varying five parameters for assessing daylight availability, and they found limits for external obstructions, in order to reach satisfactory internal levels of daylighting. Ho et al. [38] analyzed the daylight illumination of a subtropical classroom, seeking an optimal geometry for shading devices; they also evaluated the lighting power required to improve the illuminance condition within the classroom.

## 3. **Heat modulation or amortization technique (*Modify heat gains*)**

The thermal management of a building could be achieved by two methods. In the first method the thermal mass of a building (typically contained in walls, floors, partitions - constructed of materials with high heat capacity) absorbs heat during the day and regulates the magnitude of

indoor temperature swings, reduces peak cooling load and transfers a part of the absorbed heat to the ambient in the night hours. The remaining cooling load can then be covered by passive cooling techniques. In the second method the unoccupied building is pre-cooled during the night by night ventilation, and this stored coolness is transferred into the early morning hours of the following day, thus reducing energy consumption for cooling by close to 20% [39].

### *3. 1. Shifting of dayheat to night for removal*

The thermal mass of a building can be achieved either by the use of bulky construction material or by the use of additional energy intensive phase change material in the building system.

#### *3. 1. 1. Thermal mass in the construction material*

The structural mass within the existing commercial buildings can be effectively used to reduce operating costs through simple adjustments of zone temperature set points within a range that doesn't compromise thermal comfort. The cooled mass and higher on-peak zone set point temperatures lead to reduced on-peak cooling loads for the HVAC equipment, which results in lower peak energy and demand charges. The potential for using building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory and field studies [40-48]. This strategy appears to have significant potential for demand reduction if applied within an overall demand response program; because the added demand reduction from different buildings can be large.

In the summer of 2003, Xu et al. conducted a pre-cooling case study on an office building in Santa Rosa, California [48]. The research team found that a simple demand limiting strategy performed well in this building. This strategy involved maintaining zone temperatures at the lower end of the comfort range (70 °F) during the occupied hours before the peak period (8 a.m. to 2 p.m.) and floating the zone temperatures up to the high end of the comfort range (78 °F) during the peak period (2 p.m. to 5 p.m.). With this strategy, the chiller power was reduced by 80 to 100% (1 to 2.3 W/ft<sup>2</sup>) during peak hours, without having any thermal comfort complaints submitted to the operations staff. In the summer of 2004, Xu conducted pre-cooling tests along with online real-time comfort surveys, to determine occupant reactions to the thermal conditions in the Santa Rose building and in a Sacramento office building. The results of the comfort surveys in two large test buildings indicate that occupant comfort was maintained during the pre-cooling tests as long as the zone temperatures were between 70 °F and 76° F [49].

Rabl and Norford [50] developed a date-based dynamic model to simulate the effect of different thermostat control strategies for reducing peak demand. Morris et al. [45] studied two optimal dynamic building control strategies in a representative room in a large office building. The experiments showed the reduction in the peak cooling load to be as much as 40%. Keeney and Braun [46] developed a building cooling control strategy and conducted an experiment in a large office building. They found that the pre-cooling strategy could limit the peak cooling load to 75% of the cooling capacity.

#### *3. 1. 2. Thermal mass using PCM based systems*

In order to enhance the thermal storage effect of the building fabric, thermal mass with high thermal inertia, such as phase change materials (PCMs), is advised to be used. The PCM can be



integrated into the building fabric to enhance the thermal storage effect and improve the thermal comfort for the inhabitants. Generally speaking, the PCM can be integrated with almost all kinds and components of building envelopes, but different application areas have their own unique configurations and characteristics. Pasupathy et al. [51] presented a detailed review on the PCMs' incorporation in buildings, and the various methods used to contain them for thermal management in residential and commercial establishments.

Among all the PCM applications for high performance buildings, the PCM integration in wallboards, roof & ceiling, and windows is most commonly studied, due to its relatively more effective heat exchange area and more convenient implementation.

### *3. 1. 2. 1. PCM in Wallboards*

Generally, there are two ways to integrate phase change materials with building walls: "attachment" and "immersion".

"Attachment" is to attach one or several PCM integrated wallboard layers to the wall. In this case, the PCM does not constitute the material of wall, but is integrated with the attached layers beyond the wall. As the PCM is only integrated with the wallboard instead of the main wall, it can be considered as part of the indoor decoration work after the construction of the building envelopes. The separate PCM layer, such as PCM integrated gypsum board and PCM integrated composite panel, allows a separate mass production of certain wallboards by typical companies; thus, it increases the efficiency and reduces the overall cost.

Many early studies focused on the PCM playing a role as a better thermal storage mass than the traditional masonry wall in the application of collector-storage building wall ("Trombe Wall"). Benard et al. [52] began to conduct a series of experiments to compare the Trombe Wall (without natural air circulation) performance with sensible and latent materials.

Ghoneim et al. [53] did a numerical analysis and simulation of the collector-storage building wall ("Trombe Wall") with different thermal storage mediums: sodium sulphate decahydrate, medicinal paraffin, P116-wax, and traditional concrete. Their simulation compared the performances (mainly investigating the parameter of Solar Saving Fraction) of different Trombe walls with different wall thicknesses, ventilation conditions, thermal conductivities, PCM melting temperatures and load collector ratios.

Khalifa et al. [54] made a numerical model and simulated the performances of three thermal storage walls with different mediums: hydrated salt  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ , paraffin wax and traditional concrete, in the hot climate conditions of Iraq. Their numerical simulation results show that, in order to maintain a human comfort temperature zone, the required minimum thickness of the storage wall should be 8 cm for hydrated salt  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ , 5 cm for paraffin wax, and 20 cm for traditional concrete; the 8 cm thick hydrated salt  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  wall has the least indoor temperature fluctuations of all.

"Immersion" is to integrate the phase change materials with the construction material of the building envelope, such as concrete, bricks and plaster. There are normally three ways to immerse the PCM in the building construction material: direct immersion, macro-encapsulated PCM and micro-encapsulated PCM.

According to Sharma et al. [55] none of the applications of "direct immersion" and "macro-encapsulated PCM" has ever been successful in the commercial market. Currently, the most effective method is to immerse the "micro-encapsulated PCM" in the building structure material.

The concept of the “micro-encapsulated PCM” is the encapsulation of polymer/membrane, and the dimension of each “micro-capsule” is generally a few micrometers. This kind of micro-encapsulated PCM effectively avoids the shortages of the macro-encapsulated or directly immersed PCM, such as the problem of poor handling, leakage, shape-distortion and hard maintenance. There have already been many commercial products of the micro-encapsulated PCM, such as the Micronal® PCM [56] produced by a German company BASF.

Cabeza et al. [57] conducted a series of experiments on the energy storage and “thermal buffer” effect of PCM immersed concrete walls. They built two full-scale concrete cubicles under the climate of Puigverd of Lleida, Spain, in Spring and Summer time, one with traditional concrete, and the other with PCM (they used the aforementioned commercial product of microencapsulated Micronal® PCM) immersed concrete. The comparative experiments show that the cubicle with the PCM immersed concrete presents a better thermal inertia and less indoor temperature fluctuations than the other without the PCM. Moreover, their testing results also show that if the windows are opened, the thermal inertia effect will not be so obvious. Thus, Cabeza et al. additionally suggested a conclusion that the effectiveness of PCM is also influenced by the user behaviour. Zhang et al. [58] studied the thermal storage and nonlinear characteristics of the PCM wall board, and concluded that the most energy efficient approach of applying the PCM in a solar house is to apply it to the internal wall rather than exterior surface.

### 3. 1. 2. 2. PCM in roof & ceiling

The PCM assisted ceiling system is more utilized in building applications due to its easier installation and implementation with the envelope. In order to achieve thermal storage capacity approximately equal to the heat gains within the space during the daily cycle and to incorporate this system in a light weight and retrofitted building, a new concept of a ceiling panel was developed by Koschenz and Lehmann [59]; their ceiling panel is made of a mixture of a micro-encapsulated PCM and gypsum. Furthermore, capillary tubes and aluminum fins are incorporated into the thermal mass to enhance the heat transfer processes. During the daytime of occupancy, the PCM ceiling panel is directly exposed to the indoor heat sources and functions as a heat sink, while during the nighttime the absorbed heat can be released by the circulation of cold water in the capillary tubes or by the night air ventilation.

Griffiths and Eames [60] set up a test chamber with the PCM slurry (40% concentration of the micro-encapsulated PCM with water) assisted chilled ceiling system, and compared it with the situation using chilled water as the heat transfer fluid. The testing results in their experiments show that, with higher heat capacity, the PCM slurry can be circulated at a much lower flow rate than water as the heat transfer fluid; thus the energy consumption and the system noise can both be reduced without compromising the cooling effects.

Wang and Niu [61] proposed a chilled ceiling system assisted by the micro-encapsulated PCM slurry, as shown in Fig. 2. The chilled water in the traditional air-conditioning system has been replaced by the PCM slurry, which was a solution of micro-encapsulated PCM (hexadecane) with pure water in Wang and Niu’s research. During the operating hours, the chilled PCM slurry is pumped through the ceiling panel and melted during the heat exchange processes with the warm air in the room. The liquefied PCM medium will thereafter return to the PCM slurry storage tank to mix with the other chilled PCM slurry. Wang and Niu also simulated and compared the chilled ceiling air-conditioning system with three different heat transfer mediums flowing through the

ceiling panel: PCM slurry (with PCM slurry storage), water-ice slurry (with ice-water storage), and traditional chilled water (without thermal storage). The simulation results show that the system assisted by the PCM slurry has the highest efficiency, and the economical feasibility is also favorable, especially for low day/night electricity tariff ratios.

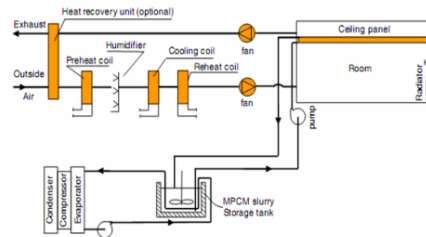


Fig. 1. A brief schematic of the chilled ceiling system assisted by the micro-encapsulated PCM slurry.

Some applications, however, do not directly integrate the PCM into the ceiling board, but equip PCM storage tubes or heat pipes beneath the ceiling or with the false ceiling. A UK company “PCM Products Ltd (2010)” [62] has made many commercial applications of PCM-unit equipped passive cooled ceilings. For example, they installed PCM storage units / heat pipes beneath the ceilings for office buildings in Nottingham University, as shown in Fig. 3. The configurations of different applications might be variable, but their basic principles are more or less the same.

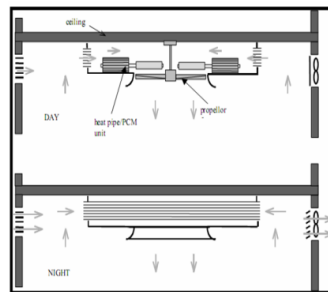


Fig. 3. PCM storage units / heat pipes beneath the ceilings for office buildings in Nottingham University: The schematic of the basic principles during day-time and night-time modes.

Pasupathy et al. [63] constructed an experimental setup consisting of two identical test rooms, to study the effect of having a PCM panel in the roof for the thermal management of a residential building. One room is constructed without the PCM on the roof to compare the thermal performance of an inorganic eutectic PCM which has a melting temperature in the range of 26-28°C. A numerical model was also developed by them and the results of the model were validated with the experimental results, and several simulation runs were conducted for the average ambient conditions for all the months in a year, and for various other parameters of interest. Pasupathy and Velraj [64] recommended a double layer PCM concept in the roof to achieve year round thermal management in a passive manner.

### 3. 1. 2. 3. PCM in glass windows

From the above descriptions of the PCM applications, it is seen that most of the studies and applications have focused on the “opaque” part of the building envelopes, such as walls, ceilings, and floors. However, it is noticed that the “transparent” part of the building envelopes, i.e., the window, has a much lower thermal resistance than other parts of the envelopes. Very few researchers have investigated “PCM filled glass windows” due to the characteristics of the PCM and its relatively difficult implementation. Ismail and his coworkers did a series of theoretical and experimental studies on composite and PCM glass systems [65-67]. The test rig of Ismail and his coworkers’ experiment is shown in Fig. 4. The whole system is mainly composed of five parts: the control system, PCM tank, electrical pump, thermocouples, and tested glasses. The components of the control system, thermocouples and the electrical pump constitute the feedback system. When the thermocouples have monitored certain interior or exterior temperatures (preset by the control system), the feedback system will automatically turn on the electrical pump, and fill the gap between the glasses with a certain PCM liquid from the PCM tank [65]. In the papers of Ismail and his coworkers, both the summer and winter modes of the test rig of this PCM filled window have been introduced [65-67]. A well designed PCM window system for the winter mode has the characteristic, that the PCM layer is completely solidified before the exterior temperature starts to increase [65]. Similarly, a well designed PCM window system for the summer mode has the characteristic, that the PCM layer should be completely liquefied before the exterior temperature starts to decrease [66, 67].

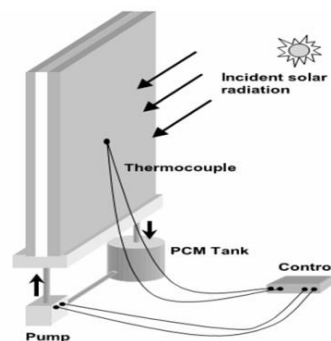


Fig. 4. The experimental test rig of the PCM filled glass windows [69].

### 3. 2. Use of night coolness for day cooling

Night ventilation techniques are based on the use of the cool ambient air to decrease the indoor air temperature as well as the temperature of the building’s structure. The cooling efficiency of night ventilation is based mainly on the relative difference between indoor and outdoor temperatures during the night, the air flow rate, the thermal capacity of the building, and the efficient coupling of the air flow and thermal mass.

In recent studies [68-76], night ventilation techniques have been applied successfully too many passively cooled or low-energy buildings, particularly in European countries. Several studies reported the results of the monitoring of passive cooling performances applied in different types of buildings [77-79].

It is evident that the performance of night ventilation depends on the ambient climatic conditions as well as the physical parameters of the building, such as the air exchange rate and thermal storage capacity. Hence, it is essential to examine the effectiveness of the night ventilation technique in different climatic regions. As before, there are many studies on night ventilation, but experimental and theoretical studies on the appropriateness of the technique in the tropics have not been documented properly.

Givoni [80] carried out comprehensive experimental studies on night ventilation techniques in Israel and Pala, California. Based on the results in California, he argued that, if effective night ventilation can be ensured by the provision of exhaust fans, high mass buildings can be more comfortable, especially during the daytime hours than lightweight buildings, even in hot-humid regions.

Blondeau et al. [81] analyzed the experimental results and showed that night ventilation succeeded in decreasing the diurnal indoor air temperatures from 1.5 to 2.8°C, even when the averaged daily air temperature range was around 8.4 °C.

Shaviv et al. [82] examined the influence of thermal mass and night ventilation on the maximum indoor air temperature in summer in Israel, and suggested that the daily air temperature range should be greater than 6 - 8°C, in order to achieve an effective reduction in the daytime peak air temperature of 3 - 8°C.

Carrilho da Graca et al. [83] carried out numerical simulations to evaluate the performance of both daytime and night ventilation for a six-storey apartment building in Beijing and Shanghai. The results indicate that night ventilation is superior to daytime ventilation in both the cities. Nevertheless, it was found that the above two ventilation strategies cannot work efficiently in Shanghai during the warm period, due to the small daily air temperature range and high air temperature and humidity.

Santamouris and Wouters [84] said that night ventilation is suitable for areas with a high daily air temperature range, and where night-time air temperature is not so cold as to create discomfort. However, since the required daily air temperature range would depend on other parameters, such as the air exchange rate and thermal storage capacity of the building, it may be difficult to set the optimum value for the daily air temperature range alone. In fact, the proposed daily air temperature range for achieving enough cooling effect of night ventilation varies among researchers.

Wang and Wong [85] investigated the impact of various ventilation strategies and façade designs on indoor thermal environment for naturally ventilated apartments in Singapore. The study concluded that night ventilation is not as effective as full-day ventilation with low thermal conductance or little thermal inertia, but with good heat conductance and fair thermal inertia, indoor conditions with night ventilation are slightly better than those with full-day ventilation.

Guobing Zhou et al. [86] studied numerically the effect of shape-stabilized phase change material (SSPCM) plates combined with night ventilation in summer. A building in Beijing without active air-conditioning is considered for analysis; it includes SSPCM plates as inner linings of walls and the ceiling. Unsteady simulation was performed using a verified enthalpy model with the time period covering the summer season, and the results of their parametric studies were reported.

Tetsu Kubota et al. [87] investigated the effectiveness of night ventilation techniques for residential buildings in the hot-humid climate of Malaysia. They concluded that the indoor humidity control during the daytime, such as by dehumidification, would be needed when the

night ventilation technique is applied to Malaysian terraced houses. Otherwise, full-day ventilation would be a better option compared with night ventilation.

Artmann et al. [88] conducted an experimental investigation to study the heat transfer characteristics during night-time ventilation. They reported that one parameter essentially affecting the performance of night-time ventilation is the heat transfer at the internal room surfaces. Increased convection is expected due to high air flow rates, and the possibility of a cold air jet flowing along the ceiling, but the magnitude of these effects is hard to predict. A design chart is proposed by them to estimate the performance of night-time cooling during the early stage of building design.

Santamouris et al. [89] presented the analyses of energy data from two hundred and fourteen air conditioned residential buildings using night ventilation techniques. The whole analysis contributes towards a better understanding and evaluation of the expected energy contribution of night cooling techniques.

#### **4. Heat dissipation technique (*Remove internal heat*)**

In many cases, the avoidance and modulation of heat gains cannot maintain indoor temperatures at a control level. A more advanced cooling strategy includes heat rejection to heat sinks, such as the upper atmosphere and the ambient sky, by the natural processes of heat transfer. The design of a building is a very important factor which influences the cooling potential of a natural cooling technique. Natural cooling refers to the use of natural heat sinks for excess heat dissipation from interior spaces, including: natural ventilation, evaporative cooling, ground cooling and radiative cooling, and also the use of a PCM based system for free cooling.

##### *4. 1. Natural ventilation*

Natural ventilation is the most important passive cooling technique. In general, the ventilation of indoor environments is also necessary to maintain the required levels of oxygen and air quality in a space. Traditionally, ventilation requirements were achieved by natural means. In the majority of older buildings, infiltration levels were such as to provide considerable amounts of outdoor air, while additional requirements were satisfied by simply opening the windows.

Modern architecture and the energy-conscious design of buildings have reduced air infiltration to a minimum, in an attempt to reduce its impact on the cooling or heating load. Better construction has resulted in buildings being sealed from the outdoor environment. In particular, the construction of large glass office-buildings, which do not allow the opening of windows, has further eliminated the possibility of using natural ventilation for supplying fresh air to indoor spaces. The successful design of a naturally ventilated building requires a good understanding of the air flow patterns around it and the effect of the neighboring buildings. The objective is to ventilate the largest possible part of the indoor space. The fulfillment of this objective depends on the window location, interior design and wind characteristics.

##### *4. 1. 1. Wind-driven cross ventilation*

Wind-driven cross ventilation occurs via ventilation openings on opposite sides of an enclosed space. Fig. 5 shows a schematic of cross ventilation serving a multi-room building. The building floorspan depth in the direction of the ventilation flow must be limited to effectively remove the heat and pollutants from the space by typical driving forces. A significant difference in wind

pressure between the inlet and outlet openings and a minimal internal resistance to flow are needed to ensure sufficient ventilation flow.

Awbi [90] investigated the air movement and the distribution of CO<sub>2</sub> in a naturally ventilated office room and an atrium, using computational fluid dynamics. The results showed that natural ventilation is capable of achieving acceptable CO<sub>2</sub> levels. Raja et al. [91, 92] have carried out a field study of the thermal comfort in naturally ventilated office buildings in Oxford and

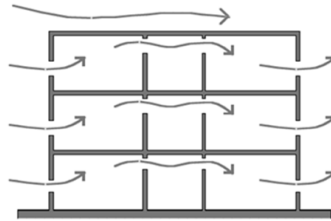


Fig. 5. Concept of wind driven cross ventilation system.

Aberdeen, UK. Their studies are focused to find the effect of controls in modifying the indoor thermal conditions. They have concluded that cross ventilation with control settings plays a significant role in lowering the indoor temperature.

Sinha et al. [93] numerically analyzed the room air distribution with or without buoyancy effects for different inlet or outlet configurations for cross ventilated rooms.

Ayad [94] studied the ventilation properties of a room with different opening configurations. The model is verified by comparing the results of steady two dimensional flows around a long square cylinder immersed in the atmospheric boundary layer with the experimental values. These analyses have been taken as a reference to model the computational domain for the atmospheric air flow around the model room.

Nikas et al. [95] studied the numerical three-dimensional prediction of the induced flow patterns around and inside a building, which is cross-ventilated in a natural way. They have given a detailed description of the natural ventilation process, whilst additional information regarding the induced velocity and pressure field is presented. Finally, the impact of the inner topology of the building on the induced flow field is investigated.

#### 4. 1. 2. Buoyancy-driven stack ventilation

Buoyancy-driven stack ventilation or displacement ventilation (DV) relies on density differences to draw cool, outdoor air in at low ventilation openings and exhausts. Fig. 6 shows the schematic of stack ventilation for a multi-storied building. A chimney or atrium is frequently used to generate sufficient buoyancy forces to achieve the needed flow. However, even the smallest wind will induce pressure distributions on the building envelope that will also act to drive the airflow.

Seppanen et al. [96] compared the displacement and conventional mixing ventilation systems in commercial buildings in the United States, by using the DOE-2.1C building simulation program. The study analyzed the north, south, and core zones of the buildings in four representative US climates. The results showed that displacement systems generally yielded

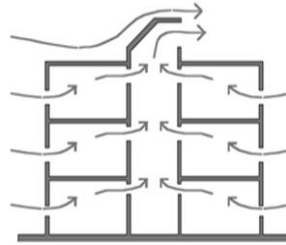


Fig. 6. Concept of buoyancy driven stack ventilation system.

superior air quality and thermal comfort, compared to conventional mixing systems operated with recirculation.

Mundt [97] demonstrated that in a room with a DV system, a person can be exposed to good quality air in a breathing zone, even if this zone was in a polluted layer. The convective plume around a body broke through the polluted layers, and very rapidly increased the local ventilation effectiveness. The displacement ventilation served as a demand controlled system for clean air from the lower part of the room.

Gan and Riffat [98] investigated the performance of a glazed solar chimney for heat recovery in naturally-ventilated buildings, using the CFD technique. The CFD program was validated against experimental data from the literature, and good agreement between the prediction and measurement was reported. The predicted ventilation rate is found to increase with chimney wall temperature and heat gain.

Mundt [99] evaluated particle transportation and ventilation efficiency with non-buoyant pollutant sources in a displacement-ventilated room.

Yang et al. [100] applied a computer model to simulate the distribution and time history of pollutant concentrations in a mockup office. They have studied three ventilation methods, namely, a DV and two mechanical ventilation (MV) systems using a side grille, and a ceiling square diffuser. Pollutant sources were assumed to be at the floor level, one with a constant emission rate and the other a fast decaying source (volatile organic compound emissions from a wood stain). Simulation results showed that different ventilation methods affected the pollutant distribution within a room. When the pollutant sources were distributed on the floor and not associated with a heat source or initial momentum, the displacement ventilation behaved no worse than a perfect mixing system at the breathing zone.

He et al. [101] studied the displacement ventilation in a room both by experimental and numerical methods. The results showed that the source type and location affected the exposure distributions for both point source and area source cases. Even when the contaminant source was at the floor level, a DV system can still generate a slightly lower concentration at or below the breathing zone, compared to an MV system. Zhang et al. [102] used a validated computational fluid dynamics program, to investigate and compare the performances of the displacement and mixing ventilations under different boundary conditions. A comparison with the conventional MV system showed, that with proper design, installation, maintenance and operation, the DV system can maintain a better IAQ, especially at the breathing zone. The numerical results showed that the air was younger at the breathing zone with the DV system than with the MV system. The CO<sub>2</sub> generated by the occupants was also easier to be expelled in the DV cases. The total volatile



organic compound (TVOC) concentration in the occupied zone was well below the limits for both the mixing and DV modes, while the contaminant levels showed a very small difference between the two ventilation modes.

Yukihiro Hashimoto [103] studied the temperature field in a modeled office room for a displacement ventilation system, using a three-dimensional CFD, and the result showed that the thermal comfort in a typical office room is maintained by regulating the supply air velocity as well as the temperature, and the stratification profiles in the room depend especially on the supply air velocity.

Guohui Gan [104] studied the simulation of the buoyancy-driven natural ventilation of buildings; two computational domains were used for the simulation of the buoyancy-driven natural ventilation in vertical cavities, for different total heat fluxes and wall heat distributions. The results were compared between cavities with horizontal and vertical inlets. The predicted ventilation rate and heat transfer coefficient were found to depend on the domain size and inlet position, as well as the cavity size and heat distribution ratio.

Ding et al. [105] examined the possibility of using the solar chimney concept for natural ventilation and smoke control. The proposed prototype is an eight-storey building with a solar chimney on top of the atrium. Reduced scale model experiments and CFD analysis were conducted. As a result, when the area ratio of the outlet to the inlet is greater than 2, the air change rate of the utility space reaches over 2 times per hour. In an event of a fire breaking out in the atrium, the neutral pressure plane of the smoke layer was found to stay inside the chimney. Hence, smoke infiltration into adjacent spaces, used for evacuation, is prevented.

Mathur et al. [106] evaluated the possibility of making use of solar radiation to induce room ventilation in hot climates. The theoretical results of the proposed model were in good agreement with the experimental ones. They found out that the air flow increases linearly with the increase in solar radiation or the air gap between the absorber and the glass cover.

Macias et al. [107] presented a practical approach to improve the passive night ventilation in social housing by applying the solar chimney concept.

Chungloo and Limmeechockai [108] studied the effect of a solar chimney and water spraying over a roof, on natural ventilation. When the ambient temperature was 40 °C, they achieved a maximum of 3.5 °C reduction in temperature in the case of a separate chimney, and a maximum of 6.2 °C reduction in temperature by the combined effect of a solar chimney and water spraying. Also, they reported that the temperature difference between the inlet and outlet of the solar chimney tends to decrease during the period of high solar radiation and high ambient temperature. On the other hand, water spraying increases the temperature difference, and consequently, the air flow rate through the chimney.

Mathur et al. [109] investigated the effect of using a solar chimney for enhancing natural ventilation. They found that there was a tradeoff between the absorber inclinations and stack height. Experiments showed that the optimum absorber inclination angle varies from 40° to 60°, depending on the latitude of the place. They compared the experimental results with the proposed mathematical model and found good agreement between the two.

Mathur et al. [110] studied the performance of different types of solar chimneys. First they investigated the performance of a cylindrical chimney, when it is covered with a transparent cover and when it is uncovered. They found that the mass flow rate increases for the covered one. Then they studied the effect of inclination on a solar chimney, and concluded that an angle of 45° yields a higher rate of mass flow rate when compared with the vertical chimney.

Burek and Hebab [111] studied the effect of varying the solar intensity, provided by an electric heater, from 200 to 100 W/m<sup>2</sup>, and the channel depth on mass flow rate through the channel. Temperatures and velocities were recorded and the mass flow rate was correlated to the heat input as  $m \propto Q^{0.572}$  and to the channel depth as  $m \propto S^{0.712}$ .

Ramadan Bassiouny and Koura [112] have done an analytical and numerical study on the solar chimney for room natural ventilation, and found that the chimney width has more significant effect on the ACH compared to the chimney inlet size. The correlation was found for the average absorber temperature and air exit velocity in terms of the intensity of solar radiation with an accepted range of approximation error.

Martí-Herrero and Heras Celemin [113] proposed a dynamical model to evaluate the energy performance of a solar chimney with a 24 cm concrete wall as storage surface for solar radiation as shown in Fig. 7. The results obtained with the proposed model are coherent with several models' response and experiments reported on solar chimneys. In addition, the difference between the proposed model and others is the incorporation of an unsteady state and the inclusion of thermal inertia.

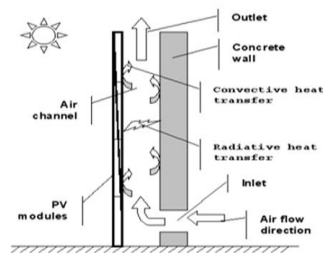


Fig. 7. Design of a solar chimney with thermal mass and PV modules.

Zamora and Kaiser [114] studied a mixed buoyancy-wind driving induced flow in a solar chimney for building ventilation numerically, and the numerical results were presented for various parameters of interest.

Due Wei et al. [115] studied the ventilation performance of a series of connected solar chimneys integrated with typical two-floor houses. Specifically, the effects of the total length and width of the chimney, the inclined angle of the second floor inlet, the length ratio of the vertical to inclined section, and the chimney inclined angle on the chimney ventilation performance, were numerically studied.

Wardah Fatimah Mohammad Yusoff et al. [116] proposed a solar induced ventilation system as a feasible alternative in enhancing stack ventilation. They investigated the effectiveness of a proposed solar induced ventilation strategy, which combines a roof solar collector and a vertical stack, in enhancing the stack ventilation performance in hot and humid climates. The results are presented and discussed in terms of two performance variables: air temperature and air velocity. The findings indicate that the proposed strategy is able to enhance stack ventilation, both in semi-clear and overcast sky conditions, and the findings also showed that the wind has a significant effect on the induced air velocity by the proposed strategy.

#### 4. 1. 3. Single-sided ventilation

Single-sided ventilation typically serves single rooms, and thus, provides a local ventilation

solution. Fig. 8 shows a schematic of single-sided ventilation in a multi-room building. The ventilation airflow in this case is driven by room-scale buoyancy effects, small differences in envelope wind pressures. Consequently, the driving forces for single-sided ventilation tend to be relatively small and highly variable.

Guohui Gan [117] has numerically predicted the effective depth of fresh air distribution in rooms with single-sided natural ventilation. Jiang and Chen [118] compared several CFD models and found that for single sided ventilation, it is important to obtain instantaneous flow information, in order to correctly predict the ventilation rate and air change effectiveness. Reynolds Averaged Navier Stokes (RANS) modeling could not correctly calculate the ventilation

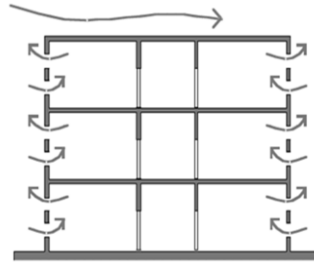


Fig. 8. Concept of single-sided ventilation system.

rate in this case. Hayashi et al. [119] have analyzed the characteristics of contaminated indoor air ventilation and its application in the evaluation of the effects of contaminant inhalation by a human occupant. Eftekhari et al. [120] conducted experimental and CFD simulation studies of air flow distribution in and around single-sided naturally ventilated rooms. The objective of this research was to investigate the wind air flow patterns around a single-sided naturally ventilated test room, and also to investigate the air flow and thermal comfort distribution inside the room during both the winter and summer periods. Alloccaa et al. [121] investigated single-sided natural ventilation by using a computational fluid dynamics (CFD) model, together with analytical and empirical models. The CFD model was applied to determine the effects of buoyancy, wind, or their combination on ventilation rates and indoor conditions. For buoyancy driven flow, the CFD results are within 10% difference from the semi-analytical results. For the combined wind and buoyancy driven flow, the CFD has under predicted the empirical model results by approximately 25%. The effects of opposing the buoyancy and wind forces have also been studied.

Jiang Chen [122] used full-scale experimental and computational fluid dynamics (CFD) methods to investigate buoyancy-driven single-sided natural ventilation with large openings. The detailed airflow characteristics inside and outside of the room and the ventilation rates were measured. The experimental data were used to validate two CFD models.

Jiang et al [123] investigated the mechanism of natural ventilation driven by wind force. Detailed airflow fields, such as mean and fluctuating velocity, and pressure distribution inside and around building-like models, were measured by wind tunnel tests.

Three ventilation cases, single-sided ventilation with an opening in the windward wall, single-sided ventilation with an opening in the leeward wall, and cross ventilation, are studied.

Yin Wei et al. [124] investigated a single-sided naturally ventilated building potential model, considering a number of factors in China. This model can be used to estimate the potential of natural ventilation via local climate data and building parameters. This paper analyzed four

typical cities in different climate regions in China, and calculated the pressure difference Pascal hours (PDPH). The results showed that single-sided ventilation has fewer adaptive comfort hours than two-sided ventilation and much less ventilation volumes.

#### 4. 2. *Natural cooling*

##### 4. 2. 1. *Evaporative cooling*

Evaporative cooling is a process that uses the effect of evaporation as a natural heat sink. Sensible heat from the air is absorbed to be used as latent heat necessary to evaporate water. The amount of sensible heat absorbed depends on the amount of water that can be evaporated. Evaporative cooling is a very old process, having its origin some thousand years ago, in ancient Egypt and Persia. Modern evaporative coolers are based on the prototypes built in the early 1900s in the United States. Amer [125] has found that among some passive cooling systems, evaporative cooling gave the best cooling effect, followed by the solar chimney, which reduced inside air temperature by 9.6°C and 8.5°C, respectively.

Passive direct systems include the use of vegetation for evaporation, the use of fountains, sprays, pools and ponds as well as the use of porous material saturated with water. Trees and other plants transpire moisture in order to reject their sensible heat. The theoretical analysis of the role of plant evapotranspiration has shown, that the evapotranspiration from one tree can save 250 to 650 kWh of electricity used for air-conditioning per year [126]. One acre of grass can transfer more than 50 GJ on a sunny day, while evapotranspiration from wet grass can reduce the ground surface temperature by 6-8°C below the average surface temperature of the bare soil.

Wanphen and Nagano [127] studied the performance of roof materials on the evaporative cooling effect and found that the siliceous shale is able to reduce the roof surface temperature by about 8.63°C, as compared to mortar concrete. Erens and Dreyer [128] and San Jose Alonso et al. [129] explained that indirect evaporative cooling (IEC) provides low energy cost for air-conditioning. Joudi and Mehdi [130] investigated the application of Indirect Evaporative Cooling (IEC), to provide the variable cooling load of a typical dwelling in Iraq. Raman et al. [131] developed solar air heaters for solar passive designs that cooperate with evaporation for summer cooling.

Various types of heat exchangers which consume only the fan and water pumping power were studied theoretically and experimentally by various researchers for indirect evaporative cooling applications. These studies are summarized as follows.

Ren and Yang [132] developed an analytical model for the coupled heat and mass transfer processes under real operating conditions, with parallel counter-flow configurations. They considered the effects of spray water evaporation, spray water temperature variation and spray water enthalpy change along the heat exchanger surface in the model. El-Dessouky et al. [133], and Heidarinejad and Bozorgmehr [134] carried out experimental studies on indirect evaporative cooling, and examined two-stage indirect/direct evaporative cooling. Hettiarachchi et al. [135] investigated the effect of longitudinal heat conduction in the exchanger wall of a compact-plate cross flow IEC with the NTU method numerically. Jian Sun et al. [136] designed and developed a two stage evaporative cooling system consisting of a plate heat exchanger, and reported that the performance of the two stage cooling was found to be 1.1 – 1.2 times more than that of the single evaporative system. Heidarinejad and Bozorgmehr [137] have studied the performance of two stage evaporative cooling units tested under various outdoor environmental conditions.

#### 4. 2. 2. Ground cooling

The concept of ground cooling is based on heat dissipation from a building to the ground, which during the cooling season has a temperature lower than the outdoor air. This dissipation can be achieved either by direct contact of a significant section of the building envelope with the ground, or by injecting air that has been previously circulated underground into the building by means of earth-to-air heat exchangers.

A building exchanges heat with the environment by conduction, convection and radiation. For an ordinary building, the main mechanism is convection, since most of the building envelope is in contact with ambient air. Then comes radiation and finally conduction, since the area of the building envelope in contact with the ground is the smallest. The principle of ground cooling by direct contact is to increase conductive heat exchange. The building temperature drops, because the ground is at a lower temperature than the air during the cooling period.

Carnody et al. [138] has explained that earth-contact buildings have advantages related not only to their energy performance, but also to visual impact aesthetics, preservation of surface open spaces, environmental benefits, and noise-vibration control and protection.

Tzaferis et al. [139] have analyzed various numerical models to study the flow and thermal characteristics of the heat transfer fluid, which circulated through an earth-to-air heat exchanger, without considering the thermal capacity of the earth, and compared the results obtained from all these models. Kavanaugh and Rafferty [140] reviewed a few alternatives for the ground-loop heat exchanger design. The high cost of excessively long ground loops is one of the primary factors that may lead to the consideration of a hybrid system. Other factors include limited land area, the cost of the land, or the high cost of high-efficiency heat pumps. Kavanaugh [141] revises and extends the design procedures recommended by ASHRAE (1995) and Kavanaugh and Rafferty [140]. The revisions to the practice of a hybrid ground-source heat pump system design involve balancing the heat flow to the ground on an annual basis, in order to limit heat buildup in the borehole field. Phetteplace and Sullivan [142] described a study that has been undertaken to collect the performance data from an operating hybrid GSHP system at a 24,000 ft<sup>2</sup> (2230 m<sup>2</sup>) military base administration building in Fort Polk, La. Yavuzturk and Spitler [143] used a system simulation approach to compare the advantages and disadvantages of various control strategies for the operation of a hybrid GSHP in a small office building.

Hollmuller and his research group have carried out a lot of research on the earth-to-air heat exchanger during the last decade. Hollmuller et al. [144] have reported on more complete and dynamic models for earth-air heat exchangers. Discovered by way of an analytical study on previously described buried pipes, Hollmuller [145] studied the thermal phase-shifting concept that aims in delaying rather than dampening the daily temperature oscillation carried by the airflow, so as to have the temperature peak of the night available in the middle of the day. Hollmuller et al. [146] conducted a theoretical and experimental study to understand the basic physical phenomenon, as well as to develop lab prototypes for a complete 12 h phase-shifting of the daily meteorological oscillation. The idea consists in forcing the airflow through a packed bed, which consists of thin and homogenous heat storage particles or layers.

Zhongjian Li et al. [147] presented an experimental study of a ground sink direct cooling system in cold areas. They studied the performance parameters, such as the cooling seasonal performance factor (CSPF) and the average heat rejection rate unit depth of a borehole, and they showed that the ground sink direct cooling system (GSDCS) has great potentialities in energy saving within a specified region.

James Dickinson et al. [148] explained the application of Bivalent (dual fuel) ground source heat pump heating and cooling systems, as a way to reduce the installation costs whilst also providing considerable economic and environmental savings; the optimum system showed a > 60% reduction in the capital cost Vs a peak sized GSHP system, whilst still providing > 70% of the respective economic savings and CO<sub>2</sub> reduction.

Michopoulos et al. [149] calculated the ground heat exchanger lengths required for heating and cooling two model buildings, a residential and an office one, located in 40 different Greek cities. They suggested that the autonomous system may be used in areas with the heating degree-days in the 800-950 K-days range. In hotter climates with less than 800 heating degree-days, the GSHP system should be supplemented by a conventional cooling system, while in colder climates with more than 950 heating degree days a conventional heating system supplement is required.

#### 4. 2. 3. Radiative cooling

Radiative cooling is based on heat loss by long wave radiation emission from one body towards another body of lower temperature, which plays the role of the heat sink. In the case of buildings the cooled body is the building and the heat sink is the sky, since the sky temperature is lower than the temperatures of most of the objects on earth. This is the mechanism that allows the earth to dissipate the heat received from the sun, so as to maintain its thermal equilibrium. There are two methods of applying radiative cooling in buildings: direct, or passive radiative cooling, and hybrid radiative cooling. In the first, the building envelope radiates towards the sky and gets cooler, producing heat loss from the interior of the building. In the second case, the radiator is not the building envelope, but usually a metal plate. The operation of such a radiator is the opposite of an air flat-plate solar collector. Air is cooled by circulating it under the metal plate, before it is injected into the building. The various concepts of radiative cooling of buildings are explained below.

**Paint:** The simplest passive radiative cooling technique is to paint the roof white. White paint does not significantly affect the radiation rate at night, since both white and black paints have almost the same emissivity in the long wave range. The advantage of a white painted roof is that by absorbing less solar radiation during the day time, the temperature of the roof remains lower, and can therefore be easily cooled by radiation at night.

**Movable insulation:** Movable insulation systems are applied on the roof of buildings. They consist of an insulating material that can be moved over the roof of the building. These systems allow the exposure of the thermal mass of the roof to the sky during the night. During the day the mass is covered by an insulating layer to minimize the heat gain in the thermal mass due to solar radiation.

**Movable thermal mass:** The movable thermal mass technique is a variation of the previous one, but with an even higher cost. It requires the construction of a thermally insulated pond on the roof of the building with a movable insulation device above it. Between the pond and the roof of the building there is a gap in which the water from the pond can be canalized.

**Flat plate air cooler:** A flat plate air cooler can be used for cooling water in a loop, similar to the solar collector linked to a storage tank. This is a very simple device, looking almost like a flat-plate air solar collector without glazing. It consists of a horizontal rectangular duct. The top of the duct is the radiator, which is a metal plate. The metal plate should be covered with a material highly emissive in the long wave section of the electromagnetic spectrum, since the

remittance of metals decreases with the wavelength. A windscreen can be used to protect the radiator surface from the wind effects.

The various studies carried out by researchers on radiative cooling are summarized in this section. The simplest passive radiative cooling technique is to paint the roof white. White paint does not significantly affect radiation rate at night, since both white and black paints have almost the same emissivity in the long wave range. The advantage of a white painted roof is that by absorbing less solar radiation during day-time, the temperature of the roof remains lower and can be easily cooled by radiation at night.

Muselli [150] presented a low cost new radiative coating material ( $1/m^2$ ) allowing to limit the heat gains during the diurnal cycle for hot seasons. He studied its reflective UV-VIS-IR behavior, and compared it with that of other classical roofed materials available in industrial and developed countries. His simulation results showed that the low cost white opaque reflective roofs would reduce cooling energy consumption by 26-49%, compared to the uncoated materials for a surface temperature of  $T_O = 60^\circ\text{C}$ .

As radiant cooling uses the roof as the “cold collector”, it is applicable only to low rise buildings, especially to single storeyed buildings with flat roofs, or for cooling the top floor of a multi-storeyed building. From the climate aspect, as it depends on longwave radiation during the nights, it would be most effective in regions which have clear sky conditions during the night hours. A detailed discussion of radiant cooling systems is presented in Givoni [151, 152].

The first radiant cooling (and heating) system, and the only one commercially available is the “Skytherm” developed by Hay [153]. In this system the (horizontal) roof is made of structural steel deck plates.

A Report of Marlatt et al. [154] discusses the performance of a prototype, and several buildings heated and cooled by the “Skytherm” system, including the Atascadero building. The section of the Marlatt Report dealing with the performance of the buildings, which have applied the “Skytherm” system, is summarized in Givoni [152].

Cook [155] Bagioras and Mihalakakou [156] claimed that passive cooling resources are the natural heat sinks of planet earth. The three heat sinks of nature are the sky, the atmosphere, and the earth. Heat dissipation techniques are based on the transfer of excess heat to lower temperature natural sinks. Heat dissipation from a building to the sky occurs by long-wave radiation, a process called radiative cooling. In fact, the only means by which the earth loses heat is radiative cooling. The sky equivalent temperature is usually lower than the temperature of most bodies on earth; therefore, any ordinary surface that interacts with the sky has a net long-wave radiant loss.

Bassindowa et al. [157], and Farmahini Farahani et al. [158] investigated the experimental and theoretical applications of long-wave radiance, nocturnal radiative cooling, its potential in different climate conditions, and the effects of various parameters on this passive method.

Imarori et al. [159] explained a radiant cooling that is considered a passive cooling option and has even higher potential for energy and peak power saving. When radiant cooling is used with displacement ventilation, i.e., when ventilation air is introduced at low level, it flows by natural means to replace ventilation air; such a system has been suggested to offer quiet comfort and energy efficiency superior to that of conventional air-conditioning systems.

Prapamong Vangtook [160] showed that a cooling tower could be employed to provide cooling water for radiant cooling and for precooling of the ventilation air to achieve thermal comfort. No active cooling is required. If a more exacting condition is required, then precooling the

ventilation air with cooling water generated from active cooling can help achieve thermal comfort, superior to that of conventional air-conditioning, while substantial energy saving can still be achieved.

Mouhib et al. [161] explained how a glass substrate coated with a stainless steel-tin double layer was used to achieve the inverse greenhouse effect. Practical tests on radiative cooling were performed during clear nights using a blackbody radiator covered by the coated plate, with the glass facing the sky, and the blackbody temperature was observed to be 6 °C below that of the ambient, and the cooling power was estimated to be 27.9 W/m<sup>2</sup>.

#### *4. 2. 4. Heat dissipation through combined cooling principles.*

In recent years, in order to achieve higher efficiency in cooling, the above said cooling principles were combined in a single system and their performances were studied by various researchers. Some of the recent studies carried out are summarized in this section.

Farahani et al. [162] studied the results of an investigation on a two-stage cooling system; it consists of a nocturnal radiative unit, a cooling coil and an indirect evaporative cooler; this investigation has been carried out in the weather conditions in the city of Tehran, and the results demonstrated that the first stage of the system increases the effectiveness of the indirect evaporative cooler. Also, the regenerative model provides the best comfort conditions.

Heidarinejad et al. [163] studied a hybrid system of nocturnal radiative cooling, and direct evaporative cooling in Tehran. This system complements direct evaporative cooling, as it consumes low energy to provide cold water, and is able to fulfil the comfort conditions, whereas direct evaporative alone is not able to provide summer comfort conditions, and the results showed that the overall effectiveness of the hybrid system is more than 100%.

Heidarinejad et al. [164] analyzed a ground-assisted hybrid evaporative cooling system in Teheran. A ground coupled circuit (GCC) provides the necessary pre-cooling effects enabling a Direct Evaporative Cooler (DEC) that cools the air even below its wet-bulb temperature. The simulation results showed that a combination of the GCC and DEC systems could provide comfort conditions, whereas the DEC alone could not. Based on the simulation results the cooling effectiveness of a hybrid system is more than 100%. Thus, this novel hybrid system could decrease the air temperature below the ambient wet-bulb temperature.

Maerefat and Haghghi [165] studied a low-energy consuming passive cooling technique (solar chimney together with earth-to-air heat exchanger) to remove undesirable interior heat from a building in the hot seasons. He found that it is possible to use the solar chimney to power the underground cooling system during the daytime, without any need for electricity. Moreover, this system with a proper design may also provide a thermally comfortable indoor environment for a large number of hours during the scorching summer days.

#### *4. 3. PCM based external storage system for free cooling*

The PCM has been developed to store “coolness” for airconditioning applications. The “cold” is collected and stored in the PCM during the night and used to cool the interior of the building during the hottest hours of the day. This concept is known as free cooling. Since the temperature difference between the day indoors and the night outdoors is small, the phase change material is the best storage option. Free cooling systems perform better in a place where the diurnal temperature range is greater than 15°C. If the melting temperature of the phase change material is



at the middle of the diurnal extreme temperatures, then an equal temperature difference is available for charging and discharging.

Recently a detailed survey on the free cooling of buildings using phase change materials was carried out by Antony Aroul Raj and Velraj [166]. In addition to the various researches on free cooling, the heat transfer problems and design considerations associated with free cooling were also discussed by them. Some of the major works discussed by them are given in this section. The first experiment on free cooling/ventilation cooling was reported by Turnpenny et al [167]. In this work, the coldness of the night air is stored in the PCM and discharged during the daytime. Heat pipes are embedded in the PCM to enhance the heat transfer between the air and the PCM. The theoretical modeling of the proposed system is also done in this work. The heat transfer rate was approximately 40 W over a melting period of 19 h for a temperature difference of 5°C, between the air and the PCM. An improvement in the design of the same system was reported by Turpenny et al [168]. A ceiling fan model with three blades with a sweep diameter of 1200 mm and air movement of 3 m<sup>3</sup>/s is used. Next, comprehensive work on free cooling was done by Yanbing et al. [169]. In this work, at night, the outdoor cool air is blown through the phase change material package bed system to charge the coldness of air to the PCM. During the daytime, heat is transferred to the LHTES system, and the coldness stored by the PCM at night is discharged to the room. The air flow rate was controlled to meet the different cooling load demands during the daytime. The room air temperature is reduced in the night ventilation system because of free cooling.

The first feasibility study of a free cooling system was done by Zalba et al. [170, 171], using PCM encapsulated in a flat plate with a melting temperature of around 20-25°C. Marin et al [172] made an improvement on the experiment by Belen Zalba, by including a graphite compounded material with the paraffin PCM for heat transfer enhancement in the PCM. Nagano et al [173] studied the potential for a manganese nitrate hexa-hydrate mixture, an inorganic PCM, as a candidate for cooling to store the cold energy suitable for the free cooling temperature range. The thermal response, mass required, toxicity and corrosion properties of this material are studied in detail.

Takeda et al. [174, 175] developed a ventilation system utilizing thermal energy storage, using phase change material granules. In this work, an experimental ventilation system shown in Fig. 9, that ensures direct heat exchange between the ventilation air and the granules containing the phase change material (PCM) was fabricated and tested [176]. They embedded the PCM directly on floor boards in the form of granules of several millimeters in diameter. The PCM packed bed is permeable to air, and so it is suitable for use in floor supply air conditioning systems. Arkar and Medved [177, 178] studied the influence of the thermal property data of the phase change material on the result of the numerical model developed for a packed bed storage system used for free cooling. A packed bed numerical model was modified to take into account the non-uniformity of the PCM's porosity and the fluid's velocity, which is due to the small tube-to-sphere diameter ratio. Based on the parametric analysis, a free cooling system was suggested by Arkar et al. [179], that comprises of a single cylindrical LHTES containing an optimized diameter of spheres with an encapsulated PCM, with a small pressure drop. Medved and Arkar [180] studied the free-cooling potential for different climatic locations in Europe. The size of the LHTES was optimized on the basis of the calculated cooling degree-hours (CDH). Six representative cities were selected in Europe that covers a wide range of different climatic conditions. Based on the outcome of the experiments of Zalba et al., two different real-scale

prototypes of the air - to - PCM heat exchangers were designed and tested by Lazaro et al. [181] following the standard ANSI (ASHRAE standard 94.1-2002 method of testing active latent heat storage devices based on thermal performance). An experimental model for a real-scale prototype of a PCM-air heat exchanger is discussed by Lazaro et al. [181].

## 5. Conclusion

The recent concept of energy efficient Green buildings attracted all the scientists and building architects to switch over from the present practice of mechanical cooling to ancient methods of passive cooling methods in an efficient modern way.

It should be noted that a concept suitable for one place may not be suitable for another, if the climatic conditions are different. Hence, being highly site specific, based on the climatic zones like hot and dry, warm and humid, cold and sunny, cold and dry, composite conditions etc., the selection of various cooling methods, and the selection of buildings and the associated materials, has to be made [182-193].

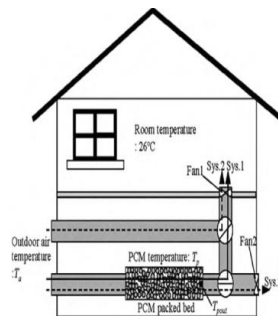


Fig. 9. Conceptual system proposed by Takeda et al. [175].

The concept of passive cooling for all the methods classified in this paper along with a detailed review provided under each category will be very useful for the building design engineers and architects to evolve with multiple concepts for a given site, while making an energy efficient design for Green buildings [194-199].

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