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Review on Passive cooling Techniques using Phase Change Materials

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Abstract: Increased environmental awareness regarding impact of green house gas emissions and CFCs lead into search of environmentally friendly cooling technologies for buildings which consume minimum or no energy. This paper reviews various passive cooling techniques by using Phase change materials. 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 paper, various methods adopted under these techniques and information regarding Phase Change materials and their desirable properties are reviewed.

Keywords: Passive cooling, Thermal Energy Storage, Phase Change Materials.

I. INTRODUCTION

Due to depletion of fossil fuels, environmental concerns like climate change, global warming, etc. there is increased attention to reduce energy consumption. About 30–40% of the world primary energy is consumed by the building sector and is responsible for one-third of green house gas emissions around the world [1]. 10–20% of energy used in buildings is used by HVAC equipments [2]. Air-conditioning systems are used to control the temperature, moisture content, circulation and purity of the air within a space. Recognizing the need to save energy and minimize the green house gases, efforts are being made to increase the awareness and importance of reducing building energy use. Global concern of the environmental impacts of the fossil fuel usage has prompted the interest to search and use passive techniques for heating and cooling of the buildings [3]. Passive cooling of the buildings refers to those technologies or techniques which are used to cool the building interior with or without minimum electricity usage. Term ‘passive’ does not exclude the cooling technologies or techniques that use fan or pump when their application might enhance the cooling performance according to some researchers [4–7]. Buildings can be cooled passively while using several natural heat sinks like ambient air, upper atmosphere, under surface soil etc. The passive cooling of buildings is broadly categorized under three sections (i). Solar and Heat Protection techniques (ii). Heat moderation and (iii). Heat Dissipation[7].

II. SOLAR AND HEAT PROTECTION TECHNIQUES (REDUCE HEAT GAINS)

This section reviews two types of heat prevention techniques namely, microclimate cooling and solar control.

A. Microclimate:

In this type of passive cooling, 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 [8].

It is very important to minimize the internal gains of a building in order to improve the efficiency of passive cooling techniques. Landscaping, Vegetation and water surface, Glazing and shading are few techniques to reduce heat gains. 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. [9].

Eumorfopoulou and Kontoleon and Kontoleon and Eumorfopoulou [10, 11] analyzed systematically the effect of the orientation and proportion (covering percentage) of plant-covered wall sections on the thermal behaviour of buildings in Greece during the summer.

Limor Shashua-Bar et al. [12] 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.

B. Solar Control:

The second method of heat prevention technique i.e. solar control can be achieved by Aperture, Glazing and Shading.In heat prevention techniques, 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 [13] 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.

Glazing is yet another method to reduce heat gains. A vast study has been done pertaining to this technique. 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 [14].

Research in the field of glazing system technology has been presented in [15-17] in which various techniques like low-emittance window systems, vacuum glazings, electrochromic windows, thermotropic materials, silica aerogels and transparent insulation materials are used.

A. Castell tested PCMs with two typical construction materials (conventional and alveolar brick) for Mediterranean construction in real conditions. For each construction material, macro-encapsulated PCM is added in one cubicle (RT-27 and SP-25 A8). The cubicles have a domestic heat pump as a cooling system and the energy consumption is registered to determine the energy savings achieved. The Experiments show that the PCM can reduce the peak temperatures up to 1^{o}C and smooth out the daily fluctuations. Reduction in electrical energy and CO_2 emissions were also recorded. [18]

Bakker and Visser [19] demonstrated that more use of solar control glazing in residential buildings in European countries can reduce the emission of up to 80 million tons of CO2, which represents 25% of the target established by the European Commission for energy savings in the residential sector in 2020. Gijón-Rivera et al. [20] made an evaluation of the thermal performance of an office on the top of a building with four different configurations of window glass, and their effect on the indoor conditions. NohPat et al. [21] 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 conventional DGU without solar control film. Ruben Baetens et al. [22] 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.

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. Ong [23] conducted an experiment where 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.

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.

The effect of daylighting and energy use in heavily obstructed residential buildings in Honk Kong was studied by Li DHW [24]. 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. [25] analyzed the daylight illumination of a subtropical classroom in Taiwan, seeking an optimal geometry for shading devices; they also evaluated the lighting power required to improve the luminance condition within the classroom.

III. HEAT MODERATION 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. 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% [26].

A. Thermal Mass:

To achieve passive cooling, Phase change materials (PCMs) are used in the building. Among all the PCM applications for high-performance buildings, the PCM integration in wallboards, roof & ceiling, and windows is most commonly used, due to its relatively more effective heat exchange area and more convenient implementation. Pasupathy et al. [27] 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.

N. A. Yahayaa and H. Ahmad in their paper, investigate the effectiveness of PCM integrated with gypsum board as ceiling panels in relation to building energy saving. The indoor air temperature of single space houses and the effect of PCM ceiling panels were predicted by using the explicit form of numerical method and specific heat capacity method respectively. The results showed that the application of PCM ceiling panels could effectively reduce the energy consumption through active cooling systems [28]. Apart from this, [29] investigates methods for impregnating gypsum wallboard with PCM.

Khalifa et al. [30] made a numerical model and simulated the performances of three thermal storage walls with different mediums: hydrated salt CaCl2 6H2O, 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 CaCl2 6H2O, 5 cm for paraffin wax, and 20 cm for traditional concrete; the 8 cm thick hydrated salt CaCl26H2O wall has the least indoor temperature fluctuations of all.

Habtamu B. Madessa reviews the literature from studies of the thermal performance of different types of PCM and different ways of integrating them into buildings. It proposes that PCMs that change phase just above normal room temperature are a promising means of reducing cooling energy demand, and improving thermal comfort in buildings. Based on this review, the paper closes with an investigation of the potential for application of PCMs in passive-house standard dwellings and office buildings in the Nordic climate. [31]

Gianpiero Evola and Luigi Marletta have presented a comprehensive study about the effectiveness of PCM wallboards for improving summer thermal comfort in existing lightweight buildings. The study is based on dynamic simulations carried out with the software 'Energy-Plus' on a sample office building. The analysis is repeated in four different locations, ranging from Southern Europe (Catania, Italy) to Northern Europe (Paris, France). The results of the simulations may help designers to make the correct choices in terms of position of the PCM wallboards, scheduled rate of nighttime ventilation and value of the peak melting temperature for the specific PCM. [32]

Sharma [33] commented that none of the applications of "direct immersion" and "macro-encapsulated PCM" has ever been successful in the commercial market. Currently, the most helpful method is to immerse the "micro-encapsulated PCM" in the building 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 type of micro-encapsulated PCM successfully avoids the shortages of the macro-encapsulated or directly immersed PCM, such as the problem of poor handling, leakage, shape-distortion and hard maintenance.

Cabeza [34] 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 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.

Zhang et al. [35] 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.

The above methods of incorporating PCM in building should be planned before construction has been started. But sometimes once the construction is started, it becomes easier to incorporate the PCM in ceilings. 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 [36]; their ceiling panel is made of a mixture of a micro-encapsulated PCM and gypsum. Furthermore, capillary tubes and aluminium 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 night-time the absorbed heat can be released by the circulation of cold water in the capillary tubes or by the night air ventilation.

E.S. Mettawee and A.I. Ead experimentally analyzed peak load shifting for air conditioning system using PCM in a room. The amount of the PCM is determined according to the cooling load of the room during the peak time. The hourly cooling load is calculated. As a result, during the peak load shifting time, which is within 2 hours, the decrease of the room temperature is between 7-10 °C by using PCM ceiling system. Consequently, it can be concluded that the PCM system is effective for the peak load shifting. [37]

Griffiths and Eames [38] 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 [39] proposed a chilled ceiling system assisted by the micro-encapsulated PCM slurry and also simulated the same. 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.

Pasupathy [40] 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. The same author in his next paper suggested a double layer PCM concept in the roof to achieve year round thermal management in a passive manner [41].

Ismail, Henriquez in their three consecutive papers, conducted theoretical and experimental studies on composite and PCM glass systems. Use of PCM in glass window is rare compared to its usage in opaque material like wall and ceilings [42-44].

B. Night Ventilation:

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.

Shaviv et al. [45] 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. [46] 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 [47] 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.

Santamouris in his another paper, [48] 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.

IV. HEAT DISSIPATION (REMOVE INTERNAL HEAT)

In some cases, reducing and modifying heat gains cannot maintain indoor temperatures at a comfortable condition. 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. It can be achieved through two methods; with and without thermal energy storage device.

Natural ventilation and Natural cooling can be done without thermal energy storage whereas Free Cooling can be achieved with the use of thermal energy storage.

A. 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. 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. 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 fulfilment of this objective depends on the window location, interior design and wind characteristics. Wind-driven cross ventilation, Buoyancy-driven stack ventilation, Single-sided ventilation are various ventilation techniques which are presented in [49-54].

B. Natural Cooling:

Natural cooling refers to the use of natural heat sinks for excess heat dissipation from interior spaces, including: evaporative cooling, and ground cooling and radiative cooling [55].

Evaporative cooling is the technology for the cooling of air by the evaporation of water. When water evaporates, it absorbs heat from the surrounding air and consequently the air is cooled. After water evaporates, it enters the air as water vapor and transmits the heat absorbed during evaporation back to the air in the form of latent heat. Therefore, the air is humidified, and the total heat, or enthalpy, of the air hardly changes. The humidified and the cooled air is used in the building for cooling purpose and the process is known as direct evaporative cooling which is most suitable in dry and hot climates [55]. In indirect evaporative cooling of the air, adding moisture to the air is avoided by separating water and air, which makes it more attractive in humid climates [56,57].

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.

Hot ambient air can be cooled down by circulating it through the heat exchanger buried at the depth of 2–3 m below the earth surface [58]. The earth surface holds a stable temperature, which is below the average ambient temperature, at the depth of 2–3 m approximately. Soil cooling implemented in desert climate may reduce the peak indoor temperature by 3^0C during hottest summer months [59].

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 [60, 61]. Radiative cooling can be achieved by Paint, Movable Insulation, Movable Thermal Mass, Flat Plate Air Cooler.

C. Free Cooling:

Free cooling is a concept developed to reduce usage of air conditioning systems, in which coolness is collected from ambient air during night and is released into the room during the hot hours of the day. Vakilatojjar and Saman [62] developed a model to analyse the phase change storage system for air conditioning applications. They found smaller air gaps and thinner PCM slabs could deliver better thermal performance. Kang [63] proposed Night Ventilation with PCM Packed Bed Storage (NVP) system. At night, the outdoor air was blown through the latent heat thermal storage system to charge coolness to PCMs, whilst in the daytime the coolness was stored by PCMs at night.

Effectiveness of this method depends upon many factors out of which most important is diurnal temperature difference. Diurnal temperature difference is the difference between maximum and minimum temperature during the day. According to [64] for the feasibility of free cooling, diurnal temperature difference at a place should be minimum 15^0C. Another one is mode of the air circulation. Some authors have proposed systems where during the day indoor air circulation is used [64,65].

Turnpenny [65] in his experimental set-up, stored the coldness of the night air in the PCM and discharged during the daytime. Heat pipes were set in the PCM to enhance the heat transfer between the air and the PCM. 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. Turpenny et al [66] in their next paper suggested an improvement in the above system. A ceiling fan model with three blades with a sweep diameter of 1200 mm and air movement of 3 m3/s is used.

One more experiment with NVP system was done by Yanbing et al. [67]. 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. [68, 69], using PCM encapsulated in a flat plate with a melting temperature of around 20-25°C. Marin et al [70] made an improvement on the experiment by Belen Zalba, by including a graphite compounded material with the paraffin PCM for heat transfer enhacement in the PCM.

In his work, A.H. Mosaffa presents numerical investigations of the performance enhancement of a free cooling system. A Thermal energy storage unit employing multiple PCMs is used. The Thermal energy storage unit is composed of a number of rectangular channels for the flowing heat transfer fluid, separated by PCM slabs. The forced convective heat transfer inside the channels is analyzed by solving the energy equation, which is coupled with the heat conduction equation in the container wall. The effect of design parameters such as PCM slab length, thickness and fluid passage gap on the storage performance is also investigated using an energy based optimization. [71]

Medved and Arkar [72,73,74] 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. Lazaro et al. [74] tested two different real-scale prototypes of the air - to - PCM heat exchangers. Dolado [75] studied PCM-air heat exchangers that allow the development of applications with technical and economical viability. In particular, using the combined technique of design of experiments and numerical simulations, the feasibility of the possible application of this type of equipment is studied and optimized for temperature maintenance in rooms. They concluded that time to reach the maximum air temperature in the room was increased (19.7%), the initial investment was reduced by 11% and the PCM melting ratio was improved by 23.2%, as a drawback, the volume occupied by the unit was increased around 3 times.

D. Phase Change Materials:

Lastly, it is important to review Phase Change Materials (PCM) as it is the integral part of free cooling principal. Phase Change Material (PCM) is a substance with a high heat of fusion, which melts and solidifies at certain temperatures, and is capable of storing or releasing large amounts of energy. The benefit of f PCM is that it enhances the thermal storage potential with a minimum change of the existing building design.

PCMs are divided into three main categories, organic PCMs, inorganic PCMs and eutectics of organic and inorganic compounds [40, 76–78]. For free cooling application, PCMs to be used for free cooling applications should posses the following properties. [33,78,80–86]:

a) Thermo-physical properties

- Melting temperature of the PCM should be in the desired operating temperature range.
- Thermal conductivity should be high to assist in charging of PCM within the limited time period.
- It should have higher latent heat per unit volume so that the storage size to store the given amount of energy is less.
- It should have high specific heat capacity that can be beneficial for the additional sensible heat storage.
- There should be small volume changes during phase change process to prevent thermal expansion of the containers.

b) Chemical properties

- PCMs should have a long-term chemical stability.
- PCMs should be non-corrosive with the container or enclosure.
- PCMs should be non-toxic, non-flammable and non- explosive.

c) Kinetic properties

- No super-cooling or sub-cooling should occur during liquefaction and solidification processes.
- It should have high crystallization rate.

A detailed study of heat and cold storage units using PCM was done by [87]. A recent paper by Farah Souayfane [88] is a comprehensive review regarding PCMs. They have presented a topology diagram to summarize the steps leading to an effective use of PCM in building applications.

Adeel Waqas [89] has given a detailed review of work conducted by different researchers on PCM based free cooling is presented. Major challenges being faced in the design of PCM based free cooling system such as phase change materials; their properties, encapsulation are elaborated and discussed in detail. This paper also provides a comprehensive list of the PCMs currently being used and that can be used potentially for free cooling applications.

An interesting and innovative database of more than 300 PCMs is presented by [90]. This database is created with the help of software, CES Selector. This database is of graet use for the selection of suitable PCM as per appliaction.

V. CONCLUSION

In this paper, a review of all passive cooling techniques is presented. If such systems are used hands in hands or directly in replacement with conventional ventilation and air conditioning systems; electricity consumption will reduce which will directly trim down the CO_2 emissions. This study will surely help researchers working in this area as well as architects while making design for energy efficient sustainable buildings.

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