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USING PHASE CHANGE MATERIALS (PCMs) FOR SPACE HEATING AND COOLING IN BUILDINGS.

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Abstract

Unlike conventional sensible thermal storage methods, phase change materials (PCMs) provide much higher energy storage densities and the heat is stored and released at an almost constant temperature. PCMs can be used for both active and passive space heating and cooling systems. In passive systems, PCMs can be encapsulated in building materials such as concrete, gypsum wallboard, in the ceiling or floor to increase their thermal storage capacity. They can either capture solar energy directly or thermal energy through natural convection. Increasing the thermal storage capacity of a building can increase human comfort by decreasing the magnitude of internal air temperature swings so that the indoor air temperature is closer to that desired over a longer period of time. Alternatively, a thermal storage unit using PCMs can be used with conventional active space heating and cooling systems to improve the overall thermal efficiency as well as to reduce the peak heating and cooling electrical load. PCMs can also be incorporated in conventional heating or cooling systems so that its capacity can be reduced. Considerable research has been done on the application of PCMs for space heating and cooling, yet at present there are limited systems in use. The paper gives a review on the research work that has been done, followed by existing systems in use and possible future directions.

Keywords: phase change materials, thermal energy storage, active and passive heating and cooling

Introduction

Thermal energy can be stored as sensible heat whereby the temperature of the storage material varies with the amount of energy stored. Alternatively, thermal energy can be stored as latent heat which makes use of the energy stored when a substance changes from one phase to another by either melting or freezing. In the latter, the storage media is known as a phase change material (PCM). Ice is an example of a 0ºC PCM.

Organic and inorganic compounds are the two most common groups of PCMs. Most organic PCMs such as paraffin waxes are chemically stable and non-corrosive, exhibit little or no supercooling properties (that is, they do not need to be cooled below their freezing point to initiate crystallisation), are compatible with most building materials, have a high latent heat per unit weight and are recyclable. Their disadvantages are low thermal conductivity, high changes in volume during phase change and flammability. Inorganic compounds such as salt hydrates have much higher latent heat per unit volume, higher thermal conductivity, are non-flammable and lower in cost in comparison to organic compounds. Potentially, they can be recycled after their useful life. However, they are corrosive to most metals and suffer from decomposition and supercooling, which can effect their phase change properties. Nucleating and thickening agents can be added to inorganic PCMs to minimise supercooling and decomposition.

Typical data of some relevant properties of thermal storage materials are given in Table 1 for comparison [1]. The masses and volumes in the table correspond to a heat storage capacity of 1000 MJ and a temperature rise of 15ºC during heat storage. The relative mass and volume occupied by each storage media is based on ice. The table shows that in comparison to other thermal storage materials such as rock or water, PCMs have a higher energy storage density, so that less material is needed. PCMs also have the advantage that thermal energy is stored and released at an almost constant temperature.

A thermal storage system may be one of the solutions to the problem when electricity supply and demand are out of phase. A building with thermal storage could shift most of the load coming from air conditioners from peak to off-peak periods. As a result, capital investment for peak power generation equipment or for upgrading the existing electrical transmission network could be greatly reduced for power utilities which could be reflected in less expensive energy prices to customers. Alternatively, thermal storage can be used to store heating or cooling that is either available for free or that can be produced very efficiently only at specific times. Thermal storage can be incorporated in buildings either passively or actively.

Cold storage using ice is a well established technology. There are a number of buildings that use ice storage systems for space cooling [2,3]. However, commercial use of other PCMs is limited.

Material	Mass (Kg)	Relative Mass	Volume (m^3)	Relative Volume
Rock	67,000	22	30	10
Water (liquid)	16,000	5.3	16	5.3
PCM (organic)	5,300	1.8	6.6	2.2
PCM (inorganic)	4,350	1.5	2.7	0.9
Ice	3,000	1.0	3	1.0

Table 1 - comparison of various thermal storage media. Stored energy = 1,000 MJ or 278 kWhr, change in temperature = 15ºC. Relative mass and volume are based on ice.

Using PCMs in walls to increase thermal mass.

One disadvantage of light weight buildings is their low thermal mass. They tend to have high temperature fluctuations, which result in high heating and cooling loads. Using PCMs in such buildings can smooth out the temperature variations [4,5].

A PCM wall is capable of capturing a large proportion of the solar radiation incident on the walls or roof of a building. Because of the high thermal mass of PCM walls, they are also capable of minimising the effect of large fluctuations in the ambient temperature on the inside temperature of the building. They can be very effective in shifting the heating and cooling load to off-peak electricity periods. One interesting possibility in building applications is the impregnation of PCMs into porous construction materials to increase thermal mass [6,7,8,9]. Gypsum wallboard impregnated with PCM could be installed in place of ordinary wallboard during construction or refurbishment of a building. It will provide thermal storage that is distributed throughout a building, enabling passive solar design and off-peak cooling. Peippo et al [6] have shown that a 120 m^2 house in Madison, Wisconsin, with a PCM wall could save up to 4 GJ a year or 15% of the annual energy cost. Also, they have concluded that the optimal diurnal heat storage occurs with a PCM having a melting temperature of 1 to 3ºC above the average room temperature. There are claims that PCM wallboard being developed could save up to 20% of the house space conditioning costs [10].

Stetiu & Feustel used a thermal building simulation program based on the finite difference approach, to numerically evaluate the thermal performance of PCM wallboard in an office building environment [11]. They found that the use of PCM wallboard coupled with mechanical night ventilation in office buildings offers the opportunity for system downsizing in climates where the outside air temperature drops below 18ºC at night. In the case of a prototype building located in California, they estimate that PCM wall board can reduce the peak cooling load by 28%. In climates where the outside temperature remains above 18ºC at night, the use of PCM wallboard coupled with mechanical night ventilation and no cooling system does not lead to energy or peak power saving opportunities. In such climates, mechanisms such as chiller-assisted space pre-cooling could be used during night and morning hours to lower the indoor air and operating temperatures.

Feustel & Stetiu also investigated using double PCM-wallboard to further increase the storage capacity of a building so that the room temperatures could be kept closer to the upper comfort limits without using mechanical cooling [12]. Simulation results for a living room with high internal loads and weather data for Sunnyvale, California, show significant reduction of room air temperature when heat can be stored in PCM-treated wallboards.

Although simulations have demonstrated the potential benefits of using PCM in walls, Feustel & Stetiu have concluded that cooling the envelope of a room by means of air transport through the room provides a very inefficient way of heat transfer. Air movement close to the walls, which determines the amount of heat being transferred, is relatively small. Particularly in periods of relatively high ambient temperatures during the night, it would be beneficial to force the supply air along the wall surfaces to facilitate good heat exchange. The limited discharge capacity of ventilation cooling during heat spells calls either for increased storage capacity or can cause the thermal storage to fail. They concluded that new ways to discharge the latent storage had to be investigated.

Other uses of PCMs in buildings

A problem with incorporating PCM in the building envelope is that it is difficult to exchange a high rate of heat between the air and the PCM. The means of air transport through the room provides a very inefficient way of heat transfer. Air movement close to the walls, which determines the amount of heat being transferred, is relatively small. An active PCM system which uses a thermal storage unit incorporating PCM and uses forced air convection as the heat transfer medium can be employed to overcome this problem.

Space cooling systems incorporating PCM have been developed that store cooling from ambient air during the night and release it indoors during hot days. Hed has investigated this type of system for building types where there is an overproduction of heat during the day time such as offices, schools and shopping centres [13]. The PCM cooler uses a 24ºC PCM encapsulated in aluminium pouches. These are placed in an air heat exchanger. The PCM is frozen at night when cool outside air is let into the building and into the PCM. The cool air is released into the building during the day. Each building was assigned with a different thermal inertia – light, medium or heavy weight. The buildings were simulated using a finite difference method. Climate data, air temperature and solar radiation on a horizontal surface were from the 2002 summer in Gavle, Sweden. The simulations show that the use of PCM has a significant effect on the maximum indoor air temperature during the day. The effects are more apparent in the light weight buildings than in the heavy buildings. The temperatures during hot summer days will rise higher in a building with a low thermal mass. The results show that by introducing the PCM it is possible to change the thermal inertia of the building. The simulations indicate that for a light weight building the amount required is about 3 to 4 kg per m^2 floor area. To achieve the same result using concrete one would need about 10 times more mass. The effect of the PCM cooler in a light weight building is similar to the same type of building with high thermal inertia. The number of hours where the temperatures exceed a desired level decreases significantly with the PCM cooler installed.

CoolDeck is a cooling system based on this principle which is commercially available [14]. The system combines the use of night ventilation with thermal storage in the building mass and/or PCM. The system can also be used in conjunction with mechanical cooling systems to reduce their size and cost. Circulating air is used to transfer heat between the room air and the building slab. The elements provide very good surface heat transfer between the circulating air and the thermal mass. The elements are attached to the slab surface in the void. The air is circulated by a fan through the narrow paths formed by sealing the edges. The turbulent air flow created through the paths enhances heat transfer between the slab surface and the circulating air. An installation at Stevenage Borough Council outside London has demonstrated this product to be a cost effective way to introduce cooling. Installation costs are approximately Aus$100 per m^2 with reductions in internal summertime temperature of 3 to 4ºC. Energy consumption is low with the electrical energy consumed by the cooling fan being 5% of the total cooling energy introduced into the building. The minimum ceiling or floor depth required is 200 mm. PCM has been integrated with the elements to increase the thermal storage performance. This has enabled the quantity of elements and interconnecting duct work to be reduced, easing coordination of existing ceiling void services. The cost of the system using PCM is approximately the same as that without, as the cost of the PCM is offset by savings due to a reduction in the number of elements and fittings. The PCM used is a salt that changes phase between 20 to 24ºC.

Farid & Husian designed and tested an electrical storage heating system which utilised off-peak electrical energy [15]. They showed that a PCM based storage unit has much less weight and could replace the conventional storage using bricks. They suggested further studies regarding the economic feasibility of the system for domestic purposes. Farid & Kong designed and tested an underfloor heating system using encapsulated PCM [16]. The PCM with a melting point of 28ºC was placed in the concrete floor during the construction. The system was able to provide uniform heating throughout the day and keep the floor surface near the desired temperature of 24ºC. In order to diminish the solar gain in buildings, Ismail & Henriquez have studied the possibility of using a window with a PCM curtain [17]. The window is double sheeted with a gap between the sheets and an air vent at the top corner. The gap can be filled with PCM so that when the outer surface is cold the PCM freezes and the temperature indoors is prevented from decreasing. Similarly, Merker et al have developed a new PCM-shading system to avoid overheating around the window area [18].

Arkar & Medved designed and tested a latent heat storage system used to provide ventilation for a multipurpose gymnasium building [19]. The spherical encapsulated polyethylene spheres were placed in a duct of a building ventilation system and acted as porous absorbing and storing media. The heat absorbed was used to preheat ambient air flowing into the living space of a building.

TEAP Energy, an Australian company that manufactures PCMs, have commercialised a 29ºC PCM that can be used for heat storage in concrete slabs for home heating [20]. This PCM has been used by Telstra and various other companies as a heat drain device on electronic systems. There is no information available on the performance of this PCM being used in buildings.

Research on PCM at the University of South Australia (UniSA)

The Sustainable Energy Centre (SEC) at UniSA is one of a small number of groups in the world working on PCM systems using forced air convection to transfer heat to and from the PCM. The work has been primarily for use in space heating and/or cooling applications, although it can be applied to other air based systems.

SEC started work with PCMs in the mid 1990's with the development of a storage unit that can be used for both space heating and cooling [21]. This was possible by using two PCMs with different melting/freezing points in series. By selecting PCMs with the appropriate melting/freezing temperature, both PCMs can be used together to store thermal energy at two temperature levels. Air is used directly as the heat transfer medium in these units. Using air as opposed to water has a number of practical advantages for a heating and cooling system, including requiring fewer components, reduced weight and cost. This first practical application of this principle was proposed for use in conjunction with a reverse cycle air conditioner and PCMs of 29ºC and 18ºC melting points. Further details on this system are given in section 5.

The SEC has developed a mathematical model for air systems using PCM storage [22]. The model considers both the melting and freezing processes and the effects of operating temperature level on the melting / freezing time. The model predicts accurately both the heat transfer rate and the outlet air temperature. This model has been extensively validated with a wide range of experimental results [23].

Work is also continuing on integrating PCM into solar photovoltaic modules in order to reduce the operating temperature and thus improving their conversion efficiency. Recent tests have demonstrated temperature reductions of more than 10ºC by incorporating a 29ºC PCM as a backing of solar modules [24]. This has been achieved by using square metal tubes filled with the PCM. A significant requirement in this research program has been to develop designs which maintain good thermal contact between the PCM and the modules in order to facilitate timely heat storage by the PCM during the day and heat loss to the environment during night time.

Two-stage PCM Energy Storage System

Figure 1 describes the night time charging and day time utilisation process during both heating and cooling seasons for a storage system comprising of two different PCMs integrated into a reverse cycle refrigerative heat pump system utilising off peak power. As the air is forced through the system it undergoes a two stage heating or cooling process. It first goes through one PCM and then the second.

The melting/freezing point of the first material is below comfort temperature, while the second material has a melting/freezing point above comfort temperature. During the heating season, the air flow is adjusted so that the system stores heat (by both materials melting) at night and releases heat at a temperature above comfort conditions (by freezing) at day time. During summer, the air flow direction is reversed and the system supplies air below comfort temperature after it is charged during night-time.

Summer night charging	from a/c ⇒ system	Low Temp. Freezing	High Temp. Freezing	To ⇒ exhaust
Summer day cooling	To ⇒ Space	Low Temp. Melting	High Temp. Melting	Hot outside ⇒ air in
Winter night charging	To ⇒ exhaust	Low Temp. Melting	High Temp. Melting	Hot air in ⇒ from a/c system
Winter day heating	Cold air in from ⇒ outside space	Low Temp. freezing	High Temp. freezing	To ⇒ space

Figure 1 - night time charging and day time utilisation process during both heating and cooling seasons for a reverse cycle refrigerative heat pump system.

The amount of reduction in the required capacity for the air conditioner and the amounts of the heating and cooling loads transferred to off peak hours have been calculated using the computer model for the storage system [21]. Annual energy cost savings has also been calculated. Using a thermal storage system containing two different PCMs can reduce the required capacity and the initial cost of air conditioner for a residential house. It also can shift a portion of the heating and cooling loads to off peak hours, when electricity cost is lower. The calculations for a typical house in Adelaide showed that a storage system consisting of 100 kg of 29ºC PCM and 80kg of 18ºC PCM, reduced the nominal rate of the air conditioner required by 50%. Also the annual electricity cost was reduced by 32% due to shifting the load to off peak time. The utility company could benefit by the shift of 52% and 41% of the air conditioning loads during the cold and the warm seasons, respectively, by reduced generation and transmission capacities if the proposed storage system is used on a large scale.

Solar heating system developed by UniSA

UniSA has developed a roof-integrated solar air heating/storage system which uses existing corrugated iron roof sheets as a solar collector for heating air [25,26]. A PCM thermal storage unit is used to store heat during the day so that heat can be supplied at night or when there is no sunshine [27,28]. In comparison to conventional heating systems, it uses less fossil fuel and produces higher ventilation rates.

Figure 2 shows the schematic of the solar heating system. The system operates in three modes. During times of sunshine and when heating is required, air is passed through the collector and subsequently into the home. When heating is not required air is pumped into the thermal storage facility, melting the PCM, charging it for future use. When sunshine is not available, room air is passed through the storage facility, heated and then pumped into the house. When the storage facility is frozen an auxiliary gas heater is used to heat the home. Adequate amounts of fresh air are introduced when the solar heating system is delivering heat into the home. Ventilation is a feature which is not currently provided by many conventional heating systems.

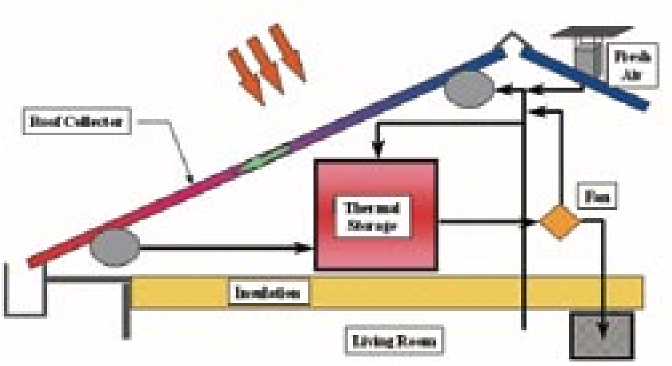

Figure 2 - schematic of the solar heating system

The solar collector is integrated into standard corrugated iron roofs (see Figure 3) [29]. Unlike other collectors, the UniSA collector does not require a change in roof design or installation. This reduces the cost and improves the aesthetics of the collector, resulting in wider acceptance of this technology amongst consumers and builders.

A model of the system for home heating was developed based on the individual models of the collector and thermal storage unit. This model used a heating load profile developed from the building modelling package, CHEETAH, developed at the CSIRO [30].

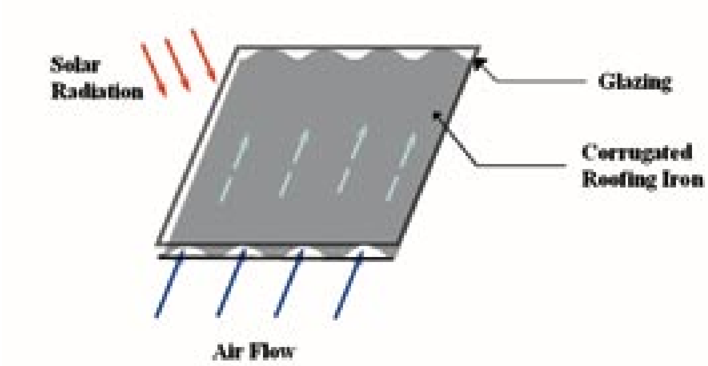

Figure 3 - roof-integrated collector

Using the model of the system together with the accumulated knowledge from the research a prototype was designed and installed in a newly built house. With the system fully installed and commissioned it is planned to operate the system for several years. A complete monitoring system has been installed which monitors temperatures. Daily wind speed levels and solar radiation levels will be taken from the Bureau of Meteorology. In addition the energy usage of the gas meter is being monitored. Ultimately the data will be used to validate and expand the model of the system and provide insight into how the system operates under real conditions.

Conclusions

There has been significant research conducted on PCMs for space heating and cooling in buildings. However, at present there are only a small number of demonstration systems in use and limited experimental data from testing PCM's in real situations.

By embedding PCMs in gypsum board, plaster, or other wall-covering materials, the building structure acquires latent storage properties. Structural elements containing PCMs can store large amounts of energy while maintaining the indoor temperature within a relatively narrow range. As heat storage takes place inside the building where the loads occur, rather than at a central exterior location, the internal loads are removed without the need for transport energy. Distributed latent storage can thus be used to reduce the peak power demand of a building, downsize the cooling system, and/or switch to low-energy cooling sources.

A problem with incorporating PCM in the building envelope is that it is difficult to exchange a high rate of heat between the air and the PCM. The means of air transport through the room provides a very inefficient way of heat transfer. Air movement close to the walls, which determines the amount of heat being transferred, is relatively small. An active PCM system which uses a thermal storage unit incorporating PCM and uses forced air convection as the heat transfer medium can be employed to overcome this problem.

Numerical studies show a significant reduction of indoor air temperature for buildings without mechanical cooling and downsizing potential as well as reduction of peak-load power and energy consumption for buildings with mechanical cooling equipment. However, latent thermal storage only performs well if the storage is periodically being discharged either by natural cooling or by mechanical cooling sources during the time of lower cooling load.

Whilst research on passive based PCM systems is continuing, it seems that active based PCM systems are being commercialised. A stand-a-lone PCM thermal storage can be a problem if space is a consideration, and so future directions of research seem to be in the development of active based PCM systems which integrate PCM into the building material or structure. ■

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