APPLICABILITY OF PHASE CHANGE MATERIALS (PCMS) FOR PEAK LOAD SHIFTING OF AIR CONDITIONING AND MECHANICAL VENTILATION (ACMV) SYSTEMS OF OFFICE BUILDINGS IN TROPICAL CLIMATES

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ABSTRACT

Air Conditioning and Mechanical Ventilation (ACMV) Systems are often used to maintain the thermal comfort and the indoor air quality in office buildings in tropical climates. These ACMVs usually account for more than 50% of the total energy consumption of the buildings. Compared to other available technologies, use of Phase Change Materials (PCMs) has been identified as an attractive innovative technology to reduce the peak cooling load and also to shift the peak cooling load to after office-hours. Temperature of building envelopes constructed using conventional materials such as bricks and concrete tend to vary with the surrounding environmental conditions, as they only absorb or release the sensible heat. On the contrary, PCMs can absorb or release much larger amount of thermal energy from/to the surrounding as latent heat, while maintaining the building envelope temperature unaffected under varying environmental conditions. Thus, conventional building envelopes accompanied with PCMs are able to significantly reduce the external heat gains into the conditioned spaces of the buildings, resulting a significant reduction in the peak cooling load. This study is mainly focused on exploring the applicability of PCMs for hot and humid tropical climates. Numerical analysis supported and validated by an experimental program and a case study revealed that by covering exterior of building envelop with 5 mm - 10 mm thick PCMs can reduce the building peak cooling load by 8% - 12%. Moreover, it was found that the peak cooling load could be easily shifted to after office hours by increasing the PCM thickness. Economic analysis showed that the PCMs with higher thermal cycles reduces the pay back periods up to 2 - 3 years and, further supported the use of low-temperature PCMs for building applications. Findings of this study recommend to incorporate the PCMs on the building envelops of the sunlit walls to reduce the peak cooling load of the building with the aim of reducing the energy consumption by the ACMV system.

Keywords: *Air Conditioning and Mechanical Ventilation (ACMV); Building Energy Consumption; Building Envelope; Peak Cooling Load; Phase Change Materials (PCMs).*

1. INTRODUCTION

Investigation of energy efficiency improvements in buildings has become one of the most significant research interests around the world today. The scarcity of natural resources, progressively increasing oil prices, carbon dioxide taxation, global warming potential and ozone depletion potential due to different materials used in building applications, make fuel economy related researches much relevant and compelling. Due to the urbanization, density of high rise buildings and sky scrapers rapidly increases and hence the use of Air Conditioning and Mechanical Ventilation (ACMV) systems are also heavily increased. ACMV systems are used to create the required thermal comfort and to provide fresh air for occupants maintaining indoor air quality. ASHRAE (American Society for Heating, Refrigeration and Air Conditioning Engineers) recommends to maintain 22°C - 27°C air temperature, 20% - 80% relative humidity and 0.25 m/s air velocity to ensure the indoor thermal comfort conditions for a hot, humid and tropical climate (ASHRAE Hand Book, 2013). As a result, more than half of the electrical energy used by a building, located in a hot and humid climate, is

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consumed by the ACMV system. According to Sri Lanka Energy Balance (2016), around 30% of total electricity consumption by the country is used for commercial sector and out of that more than 50% is used for ACMV systems; whereas, around 35% of the total electricity consumption is used for domestic sector, mainly for lighting.

Energy consumption by an ACMV system can be significantly reduced by minimizing the cooling load (or net heat gain), by optimizing the equipment selection and system design and also by introducing best practices to operate the system. Heat gain into the building can be reduced by controlling the conduction heat exchange between the building and the outside environment through walls, glazing and roof. This includes the reduction of excess ventilation, infiltration, solar radiation through fenestrations. Additionally, controlling the internal heat generation by occupants and equipment also helps to reduce the total cooling load. Intensity of heat gain due to conduction between the building and outdoor environment is highly dependent on the material properties of the building envelope.

Moreover, heat gain from conduction is immediately transferred to the room air by convection and the cooling load of the building is increased. On the contrary, heat gain by the radiation (i.e. sun and light sources) is first absorbed by the surfaces of the building. Then depending on the thermal capacities of the building envelopes, their temperature increases slowly due to absorption of radiant heat and is called 'heat storage effect'. As a result, radiation heat gains introduce a 'time lag' depending upon the surface characteristics and the heat capacity of the building envelops. Hence, total radiation heat gain by the building envelope does not immediately contribute to the cooling load of the building. Owing to this phenomenon, indoor and outdoor peak temperatures do not occur simultaneously and very often, indoor peak temperature occurs with a time delay which depends on the heat capacity of the building envelope.

In general, an office building is occupied from 8:30am to 4:30pm. Hence, power consumption by the ACMV system can be significantly reduced by shifting the peak cooling load and the peak temperature of the building to after office hours. This can be achieved by increasing the 'time lag' between the occurrences of peak indoor and outdoor temperatures. 'Time lag' can be increased by increasing the heat capacity (or heat storage effect) of the building. Therefore, this study focuses on investigating the possibilities of controlling the above time lag using Phase Change Materials (PCMs), with the aim of shifting the peak temperature and load to after office hours. To perform this, a numerical analysis on building heat gains and an economic analysis have been performed followed by a thorough review on PCM selection for building applications.

2. SELECTION OF PHASE CHANGE MATERIALS FOR BUILDING APPLICATIONS

2.1. THERMO-PHYSICAL PROPERTIES OF PHASE CHANGE MATERIALS

A substance which changes the phase when heated (or cooled) is referred to as a Phase Change Material. Solid PCMs are melted when heated and liquid PCMs are solidified when cooled. Moreover, heat is absorbed during melting and heat is released during solidification. Amount of heat absorbed by a solid PCM until it reaches to the melting temperature from a lower temperature is called the solid sensible heat. When the heat is further supplied to a solid PCM its phase is changed from solid to liquid while maintaining the temperature at the melting point (if pressure is unchanged). The heat required for the phase change is called the latent heat of melting. Once all the material is melted, if further heat is absorbed (liquid sensible heat), the temperature of the liquid material is increased until the start of next phase change (liquid to gas). The reverse process: solidification of a liquid PCM, also can be described in a similar way as shown in Figure 1. As a result, a PCM undergoes a thermal charging and discharging cycle, where it behaves as a sensible heat storage material and as well as a latent heat storage material.

One of the most important thermal properties of PCMs is to have high latent heat of fusion (melting) per unit volume (or weight) so that more heat can be absorbed (or released) for a small amount of PCM. In addition, selection of PCMs for a given application is temperature specific. To obtain the maximum use of PCMs, the phase change temperature must be in accordance with the climate, location and the application it is used. As a high thermal conductivity will allow heat to disperse through or leave a material more quickly (allowing the PCM to absorb or release heat at a higher rate), PCMs should have high thermal conductivities. To undergo many thermal charging and discharging cycles, thermal stability of PCMs should be very high and thermal properties should be reproducible during the entire life time. Moreover, the PCMs should be non-toxic, non-flammable, non-explosive and environmentally friendly. Also, they should be non-corrosive for some selected encapsulation materials (i.e. metal). Small volume change during solidification/melting is also essential to reduce the volume needed to encapsulation. The difference between the solidification and melting temperatures should be very low (preferably the same) and the irreversibility during the thermal cycles should be minimum to ensure the high efficiency of the entire process. More importantly, the selected PCM for a given application should be abundant and cheap, to obtain more economic benefits (Kalnaes, 2015).

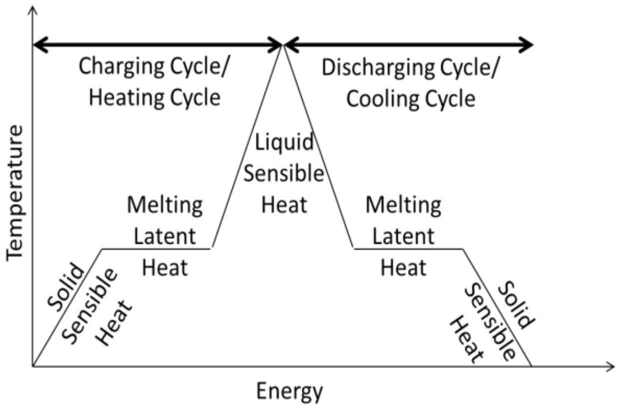


Figure 1: Thermal Cycle of a PCM
(Source: Sutterlin, 2016)

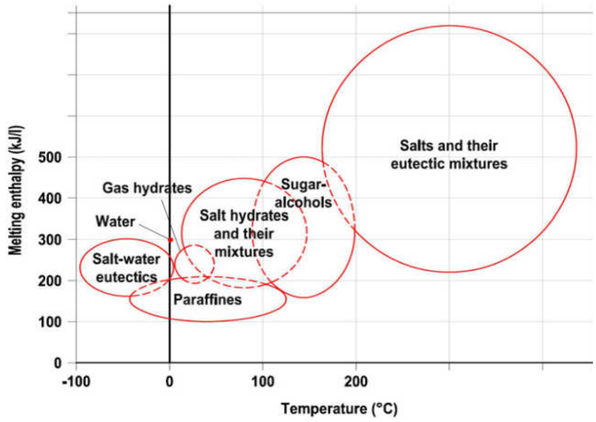


Figure 2: Melting Enthalpy and Meting Temperature of Different PCMs
(Source: Baetens, 2010)

2.2. *TYPES OF PCMS*

PCMs can be divided into three main groups based on their chemical composition: organic compounds, inorganic compounds and eutectic mixtures (or inorganic eutectics). Organic PCMs are mainly grouped as paraffins and non-paraffins i.e. fatty acids, esters, alcohols and glycols. Organic PCMs are generally chemically stable, do not suffer from super-cooling, non-toxic and non-corrosive. As shown in Figure 2, paraffins demonstrate the lowest heat of fusion among all the other PCMs. They are more promising to be employed in building applications owing to the low melting temperatures which are in the human thermal comfort zone. On the other hand, non-paraffin PCMs have high latent heat of fusion. However, there is a lack of material which melts in the human comfort region. Moreover, cost of non-paraffin PCMs are about three times higher than the paraffins PCMs. So, paraffin PCMs can be identified as one of the candidate option for building application.

Most common inorganic PCMs are hydrated salts. In general, they have the highest heat of fusion, high melting temperatures, good thermal conductivity, non-flammable and are very cheap. As majority of these materials show super-cooling and phase segregation, they are more suitable for using as thermal energy storage medium rather than in building envelope applications. Eutectic mixtures are made of mixing multiple numbers of organic and/or inorganic PCMs to obtain the best performance depending on the application, yet they are still in the research and development state (Kalnaes, 2015 and Baetens, 2010).

2.3. *SELECTION OF PHASE CHANGE MATERIALS FOR TROPICAL CLIMATE*

Identifying the optimum phase change temperature for a given application is challenging as it governs the energy performances. Using some simplified heat transfer assumptions, Peippo et.al, (1991) obtained the following formulae to determine the average temperature of the conditioned space, optimum phase change temperature and the material thickness for PCMs.

$$T_{m,opt} = T_r + \frac{Q}{ht_{stor}} \quad \textit{(Eq: 01)}$$

$$D_{opt} = \frac{t_n h}{\rho \Delta H}\left(T_{m,opt} - T_n\right) \quad \textit{(Eq: 02)}$$

$$T_r = \frac{t_d T_d + t_n T_n}{t_d + t_n} \quad \textit{(Eq: 03)}$$

where, $T_{m,opt}$ = optimal phase change temperature of the PCM (°C), T_r = average temperature of the conditioned space (°C), Q = heat absorbed per unit area of the conditioned space (J/m2), h = average convection heat transfer coefficient between wall surface and the surroundings(W/m2.°C), T_d = daytime temperature of the conditioned space (°C), T_n = night time temperature of the conditioned space (°C), t_d = charging time, day (s), t_n = discharging time, night (s), $t_{stor} = t_d + t_n$, D_{opt} = optimum thickness of the PCM (m), ΔH = latent heat of fusion of the PCM (J/kg).

Office buildings in a tropical country like Sri Lanka operate from 8:30am - 4:30pm and are maintained at 25°C and 55%RH. If the average temperature in Colombo, during the after office hours is assumed to be 29°C, then the average conditioned space temperature was found to be 27°C. Solving above expressions, the optimum phase change temperature for the above conditions was found to be 30°C. It is very obvious that the optimum PCM temperature is highly depend on the operating temperature and time of the conditioned space.

Considering the temperature of fusion, feasibility of encapsulation, availability in the market and the price, paraffins was chosen to be used in this study. Table 1 shows some important thermo-physical properties of some selected paraffins based on (Seong, 2013) and (Thermal properties of RT35HC, 2016).

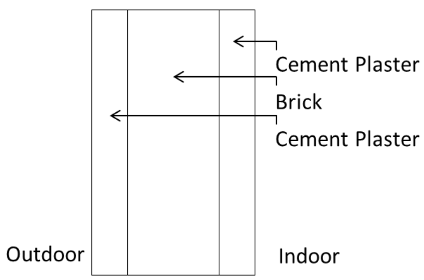
Table 1: Thermo-physical Properties of Some Paraffin PCMs

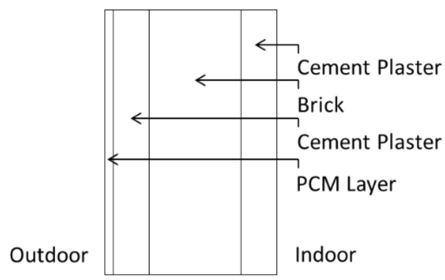
Property	**Dodecanol [Seong, 2013]**	**Octadecane [Seong, 2013]**	**RT35HC [Thermal Properties of RT35HC, 2016]**
Melting temperature (°C)	24	29	34
Conductivity (W/mK)	0.28	0.26	0.20
Density (kg/m^3)	853	777	800
Specific heat (kJ/kg.K)	1.55	1.20	2.00
Latent heat (kJ/kg)	230	235	240

3. HEAT TRANSFER ANALYSIS THROUGH BUILDING ENVELOPES

PCMs can be integrated to the building envelope at outside or inside the building wall and/or on the roof-slab of the building using PVC (polyvinyl chloride) panels or metals as encapsulations. When the PCMs are placed on the outside the building, it can reduce the heat gain into the building inner space during the day time due to the heat storage effect. On the other hand, when they are installed inside the building, it can make sure that it reduces the temperature fluctuations in the indoor environment. In addition, PCMs can be directly impregnated into porous building construction materials i.e. concrete, cement and plaster. However, this method may result leakage problems during phase change of the materials in the charging cycle. Microencapsulation has been proposed (Kuznik, 2011) to enclose the PCMs in a microscopic polymer capsule so that the encapsulated PCM powder can be mixed with other regular building construction materials. However, the encapsulation material should be carefully selected to make sure that no chemical reactions taken place with the other building materials. The volume expansion of the PCM has also to be carefully studied to make sure to minimize the crack propagation on the walls.

By analysing different integration methods as mentioned above, this study is performed assuming the tiled-PCM encapsulations are applied on the outside the building envelope to reduce the heat gain to the conditioned space as illustration in Figure 3. The equivalent thermal resistor networks for wall sections are shown in Figure 4.





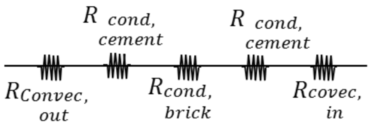


Figure 3: Building Envelope Without PCMs and Equivalent Resistance Network

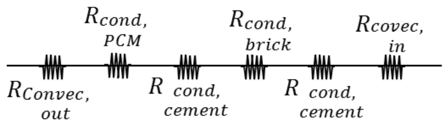


Figure 4: Building Envelop with PCMs and Equivalent Resistance Network

Thermo-physical properties of above materials and convection heat transfer coefficients of the indoor and outdoor environments are shown in Table 2.

Table 2: Thermo-physical Properties of Some Paraffin PCMs

Style Name	Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)	Thickness (mm)	Convection (W/m^2.K)
Cement Plaster	1.50	1300	1550	20	
Brick	0.60	1800	900	200	
PCM	0.26	777	1200	10	
Indoor Convection Coefficient					10
Outdoor Convection Coefficient					15

Total thermal resistances without and with PCMs were calculated and are, 0.527 °C/W.m^2 and 0.565 °C/W.m^2 respectively. Increment of thermal resistance due to PCM layer was found to be 7.2% and hence, the thermal resistance due to PCM encapsulation material was neglected due to its very low thickness.

4. ANALYSIS ON BUILDING COOLING LOAD PROFILE

Cooling load analysis was performed for a 3-story office building located in Colombo. The internal partitions of the floors and different shading methods used to reduce the external heat gains were neglected. Approximate floor area of a floor is 700 m^2. Thermal resistance due to wall paint were also neglected. The doors were double glazed swing type (2 m x 2.5 m) having 20 mm air space sandwiched between two 5 mm thick clear glasses surrounded by 50 mm width Aluminium frame with thickness is 40 mm. Windows were single clear glazed (3 m x 1.5m) having 5 mm thick glass mounted on 40 mm width and 25 mm thick Aluminium frame.

Internal heat gain of a typical floor of the building is given in Table 3. It was further assumed for a new building which has Aluminium doors and windows, the infiltration losses are negligible and the required fresh air is delivered at a centralized AHU (Air Handling Unit). 5 mm thick PCM RT35HC (Table 1) was used to perform the numerical analysis where indoor thermal conditions were maintained at 25 °C and 55% RH. Finally, the cooling load profile of the floor for with and without PCMs was obtained as shown in Figure 5.

Table 3: Internal Heat Gains

	Power (W)	Number
Desktop computers	150	20
Laptop computers	60	40
Occupants (light office work)		
Sensible	75	40
Latent	35	40
Lighting (T8-Florescent)	32	50
Refrigerator	250	1
Water heater	2000	1
Laser printer	150	2
Photo copier	300	2

From the CLTD/CLF Cooling load analysis method (Cooling Load Temperature Difference/ Cooling Load Factor Method), it was found that the peak cooling load was reduced by around 8% - 9% and peak load has been shifted approximately by an hour compared to the outside maximum temperature.

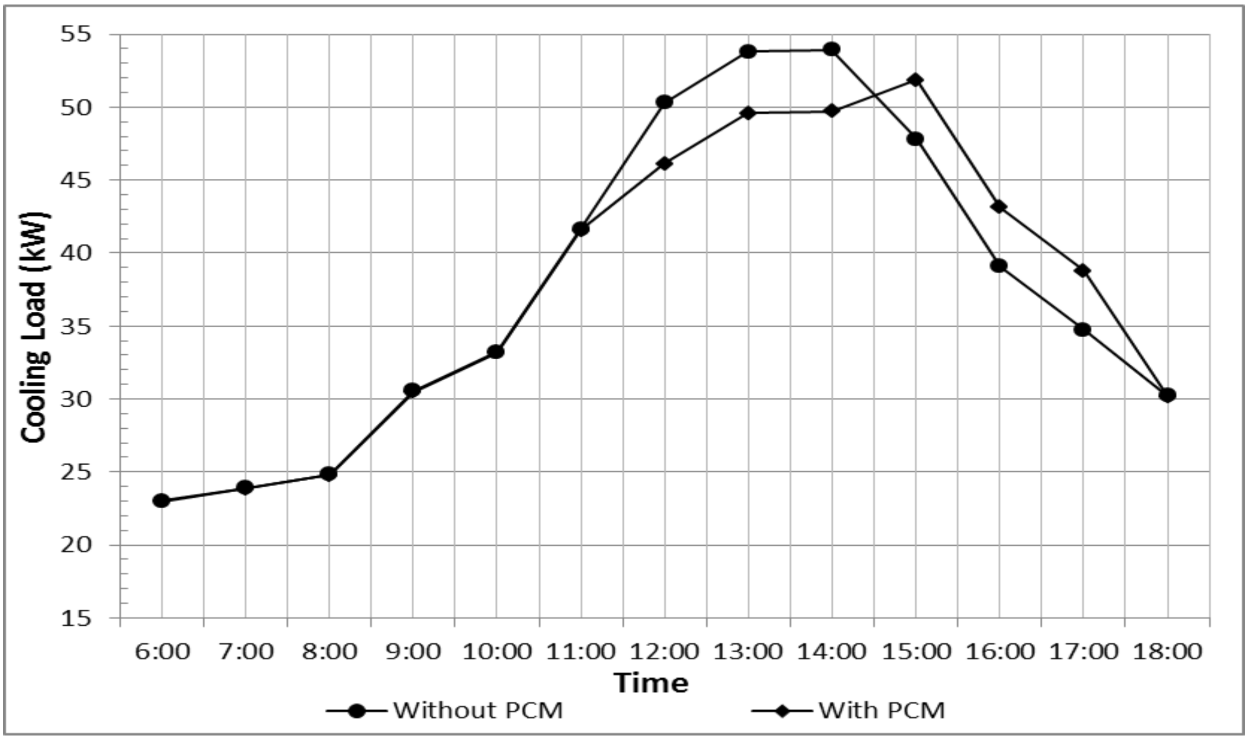


Figure 5: Cooling Load Profile of the Floor for with and without PCMs

5. ECONOMIC ANALYSIS

Commercial paraffinic PCMs are made of by-products from the oil refineries and hence available abundant at a relatively cheaper price. Depending on the purity, pure paraffin wax (purity > 99%) is the most expensive paraffin and is approximately LKR 3000/kg (Kosny, 2013).

For the present work, PCM RT35HC (purity - 95%) (Thermal Properties of RT35HC, 2016) was used and the current market price is about LKR1800 per kg. The building considered here requires around 550 kg of PCMs to cover the entire sunlit walls, having an area of 145 m^2. It was also found that around 1-5 kW can be reduced from the peak cooling load resulting approximately 60 kWh of energy saving per day. If the life time of the PCM material is around 10,000 thermal cycles, it can last approximately 25 years assuming each day it experience a thermal cycle. If the unit price of the grid electricity is LKR 20, it was found that the payback period is around 4 years, considering only the cost involvement to purchase the phase change materials.

6. DISCUSSION

As explained above, PCMs can be used to reduce and shift the peak cooling load of a building to after hours of office buildings in tropical climates. Amount of heat absorbed by the building envelope can be reduced by increasing the material thicknesses of walls. Material thickness has to be selected based on an economic analysis as un-optimized selection would lead to higher payback periods. If the peak load is reduced, then the capacity of the entire AC system will be reduced and hence, initial investment would also be reduced, in addition to the running expenses. Therefore, attractive payback periods can be obtained by implementing PCMs in building wall-envelope application.

7. FUTURE WORK

Results of the numerical analysis will be validated by an experimental program and a whole building simulation using 'e-Quest' Software. Fabrication of the experimental test rig has already started and expected to obtain the results to validate the modelling work. A CFD analysis will also be performed to understand the transient thermal characteristics of the building envelope when integrated with PCMs.

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