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Phase Change Material as an Outer Layer for Building Walls: Computational Study of Indoor Air Temperature to Facilitate the Selection Process

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Abstract - Having a layer of phase change material (PCM) around the sidewalls of a building is a one-time investment for passive cooling / heating of the indoor air. Hence it is important to know the suitability of a PCM for a specific climatic region. In this paper, the analysis of three rooms with different dimensions: shallow, tall and cubic under three different weather conditions: hot-arid, warm tropical, and, extreme cold are presented in detail. The study was performed based on the simulations carried out using EnergyPlus tool. The results and conclusions discussed in this paper give useful information which can help in the PCM selection process for different sized rooms or buildings in general.
Index Terms - building envelope, facades, phase change material, thermal comfort, and thermal energy storage.

1. INTRODUCTION

Making buildings energy efficient has been a fascinating research topic from the last few decades as heating, ventilation and air conditioning (HVAC) systems are costly and are hazardous to the environment. Among the various methods of making buildings energy efficient passive cooling or heating of the building envelope is cost effective and easy to implement on the existing buildings [1]. Use of phase change materials in the building walls to make the buildings energy efficient has been widely reported [2, 3, 4].

The PCM can absorb and store the heat energy while undergoing change of phase and hence can reduce and delay the heat transfer [5]. On one side the specific heat and thermal conductivity of the PCM can cause thermal inertia like any other material and on the other side, the latent heat absorption is beneficial for increasing the building energy savings [6]. There are several studies reporting the analysis of positioning of the PCM layer in the building walls. Chwieduk [7] analyzed numerically by placing 25 cm insulation and 1.5 cm PCM over the external walls to study the heat gains and losses through the walls by modeling the energy balance of a room considering the high latitude location country regions. In this study it was observed that the light weight insulation and PCM together of 26.5 cm thickness would provide the same thermal behavior as that of a 45cm thick brick wall which ensures that the PCM wall used in building would be suitable for high latitude countries. However, the conclusions are limited to a cubic shaped room. Childs et al. [8] considered parameters such as climate, location of PCM within the wall, PCM volume, PCM melting and freezing range in relation to the indoor set point temperature 25°C, phase change temperature, and the wall orientation investigated for the Phoenix and Baltimore climatic conditions. Their observations found that the wall cavity filled with PCM-cellulose layer entirely was the most effective one in reducing the cooling load. However, the study did not show the effect of PCM on indoor air temperature as the study was carried out only for a single wall.

Experiments analyzing the effect of macro encapsulated PCMs incorporated at three different positions: placing over the concrete walls over the inner surface, outer surface and laminating PCM in between the walls was performed over the model room built and tested for Hong Kong weather condition [9]. Their results show that the model with laminated PCM can reduce the indoor temperature by 4°C and model with inside PCM reduces the indoor humidity by 16% as compared with the model room without PCM. It was observed that the study was carried out over an almost cubic shaped room and hence the conclusions drawn may be applicable to cubic shaped rooms. Cool color coatings over the exposed surface of the PCM can reduce the building cooling load. Experimental and numerical studies carried out by Lei et al. [10] with the incorporation of cool color coating over the surface of the PCM fixed over the roof of a building located in Singapore (warm tropical climate). Cool color coating is beneficial for reflection of radiation and PCM is beneficial to reduce the conductive heat fluxes resulting in the major annual energy saving of 8.5% and a reliable monthly energy reduction of 5–12% for the complete year. The study was carried out over a model room

whose size was 70 mm x 200 mm x 130 mm. However, the effects are not checked for other dimensions where the box could have been classified as shallow, tall or cubic. Apart from this, the study was limited to understand the heat transfer through the roof.
Arıcı et al. [11] studied numerically the PCM over both inner and outer surfaces of a wall for the weather conditions of three cities of Turkey. They concluded that placing of the PCM over the outside of the wall can give maximum energy savings for heating situations and placing PCM over the wall inside face can give more energy savings for the cooling conditions. The study does not give a general information regarding the room dimensions considered as this involved the study of a single building wall. Sravani et al. [12] reported experimental study of PCM over the external wall surface with different types of claddings. Claddings filled with the PCM and composite wall cladding can enhance the energy efficiency in buildings by passive thermal storage and thermal inertia.
The PCM can be a one-time investment passive method for passive heating or cooling of buildings [1]. However, from the literature review it was learned that there are no studies that report the suitability of PCM for shallow, tall and cube shaped structures in different climatic regions. In this paper analysis of shallow, tall and cube shaped rooms having identical interior air volume with and without PCM as an outer layer for the walls is presented. Various simulations using EnergyPlus were carried out in this study. The room was primarily assumed as a class room and was analyzed for three different weather conditions: hot arid, tropical / moderate, and, extreme cold.
The main objective in the present study was to help the decision making of whether to invest on having PCM as an outer layer for a specific building or not. In this study, we analyze the influence of PCM layer on the room air temperature throughout the year and the month during which the energy consumption could be maximum. In the second section the building model and weather condition details are discussed. The simulation and results are discussed in the third section followed by conclusions in the fourth section.

2. METHODOLOGY

2.1.1. Building model and selection of climatic region
The dimensions of the reference model rooms (shallow, tall and cubic) used in the present study are as shown in figure 1. On one side, the rooms were assumed as enclosures with no doors and windows. On the other side, the roof and floor in these studies are assumed to be made of insulating material (1000 mm rock wool insulation) in order to quantify the influence of PCM on the room air temperature. The brick layer of the sidewalls is 102 mm thick. EnergyPlus version 9.1 was used for the simulations. The rooms for the 3 cases studied had following dimensions (length X breadth X height): 20 m X 15 m X 5.5 m (*shallow*), 8.2 m X 8.2 m X 18.02 m (*tall*) and 10.92 m X 10.92 m X 10.92 m (*cubic*).

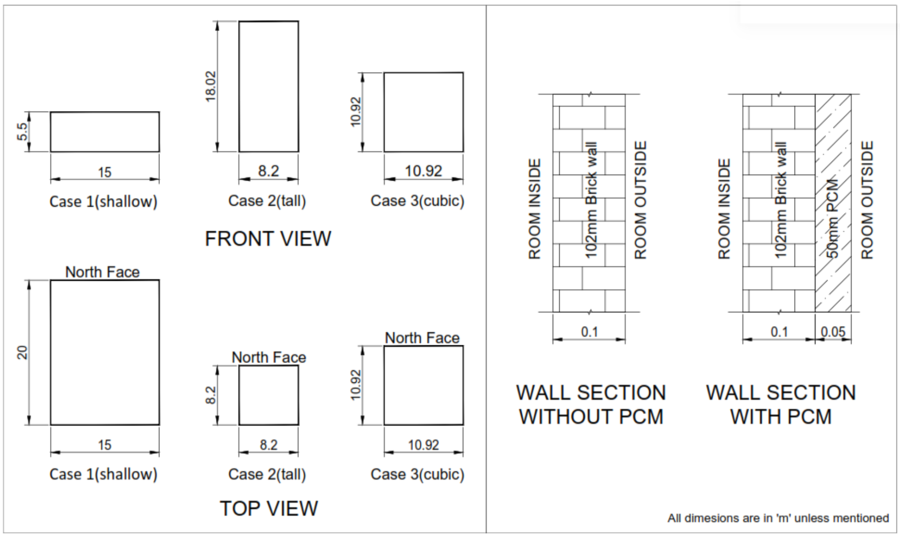


Figure 1:
Details of the dimensions of the model rooms.

Here the interior volume for all the cases has been considered same around 1025m³, case 1 considered as a shallow (H/L<1) case building, case 2 considered as a tall (H/L>1) building and case 3 considered as a cubic (H/L=1) building as shown in table 1. Floor and roof material are essentially insulated in order to understand the role of PCMs as an outer layer for the side walls. The insulation material properties chosen are given in table 2. This analysis of rooms with the same indoor air volume but with different geometric configurations subjected to different weather conditions could help us in understanding the feasibility of different phase change materials and hence infers the selection of PCM as an outer layer. On the other hand, the simulation approach used in the present work can be used as a protocol in the analysis of PCM application in building heating or cooling in general.

Description	Length - L (m)	Breadth - B (m)	Height -H (m)	H/L	H/B	Wall thickness (m)	Roof & floor thickness (m)	Interior air volume – IAV (m³)	Exterior wall area for 4 sides – EWA (m²)	Ratio $\frac{EWA}{IAV}$ (/m)
Case 1 (shallow)	20	15	5.5	0.28	0.37	0.1	1	1025.6	385.0	0.38
Case 2 (tall)	8.2	8.2	18.02	2.20	2.20	0.1	1	1025.3	591.1	0.58
Case 3 (cubic)	10.92	10.92	10.92	1.00	1.00	0.1	1	1025.1	477.0	0.47

Table 1
Details of the dimensions for shallow, tall and cubic shaped rooms.

The shallow, tall and cubical rooms are studied under three different climatic conditions:

i. Desert condition - Abu Dhabi, UAE region
ii. Warm tropical condition - Bangalore, India region
iii. Extreme cold condition - Helsinki, Finland region

This analysis can help in the decision making of the selection of suitable PCM for different ratios of wall surface area to interior air volume. The present study is useful in the contexts wherein there is limited scope for the ventilation.

The simulations were carried out with and without PCM layer for the side walls. Weather files considered for the simulation are .epw format weather files available in energyplus web resource [13].

Material thermo-physical properties are detailed in table 2. Different PCM were chosen based on the location of the room i.e., desert / warm tropical / extreme cold region. It is important to note here that the PCM chosen are commercially available [14]. The thermos-physical properties of the PCMs used in the present study are tabulated in table 3. PCMs OM32, OM50 and OM65 were considered for Abu Dhabi weather conditions; PCMs OM18, OM29 and OM42 were considered for Bangalore weather conditions; PCMs HS23N, HS10N, OM05P, OM18 and OM29 were considered for Helsinki weather conditions respectively.

Material	Brick - fired clay	1000mm Insulation	PCM HS23N	PCM HS10N	PCM OM05P	PCM OM18	PCM OM29	PCM OM32	PCM OM42	PCM OM50	PCM OM65
Roughness	Medium Rough	Medium Rough	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth
Thickness in m	0.102	1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Conductivity in W/m-K	1.34	0.03	4.976	4.25	0.37	0.182	0.293	0.219	0.19	0.21	0.19
Density in kg/m³	2400	43	1078	1057	763	906	976	926	903	961	924
Specific Heat in J/kg-K	790	1210	1580	1900	5950	2920	2320	3200	2710	3330	2830

Table 2
Thermo-physical properties of materials of various elements of the building envelope.

Material	PCM HS23N	PCM HS10N	PCM OM05P	PCM OM18	PCM OM29	PCM OM32	PCM OM42	PCM OM50	PCM OM65
Temperature 1 in ℃	-23	-13	3	15	25	29	41	50	65
Enthalpy 1 in J/kg	2000	3000	9000	17000	11000	9000	5000	13000	16000
Temperature 2 in ℃	-22	-12	4	16	27	31	42	51	66
Enthalpy 2 in J/kg	7000	8000	22000	18000	27000	19000	9000	17000	24000
Temperature 3 in ℃	-21	-11	5	17	28	33	43	52	67
Enthalpy 3 in J/kg	170000	32000	62000	27000	37500	25000	18000	25000	37000
Temperature 4 in ℃	-	-10	-	18	-	-	44	53	68
Enthalpy 4 in J/kg	-	195000	-	50000	-	-	59000	32000	52000

Table 3
PCM enthalpy (latent heat) values at different temperatures (it should be noted that there is no change in enthalpy outside the given temperature boundaries).

2.1.2. Details of internal loads

In all the three cases the test room considered as an average sized classroom with 65 occupants. The energy consumed due to lighting is assumed as 13.35 W/m² and due to a single projector as 350W. The working hours are assumed from morning 08:00 AM till evening 05:00 PM of the day. During the non-working hours the internal load is zero.

2.1.3. Mathematical model and simulation details

EnergyPlus was used to carry out simulations in the present work. For the case of thermal performance study with PCM walls on all sides (North, East, South & West) surface convection algorithm based on temperature difference was used: TARP algorithm for inside and DOE-2 algorithm for outside convection. Conduction finite difference algorithm was used as a heat balance algorithm.

The temperature difference and net heat transfer rates are estimated in hourly time step to compare the feasibility of different PCM's if used in the three different weather conditions of the cities mentioned earlier. Site locations are defined in the energyplus input data file editor where the information available from weather data files are provided with reference to latitude (in deg), longitude (in deg), time zone (in hr) and elevation (in m).

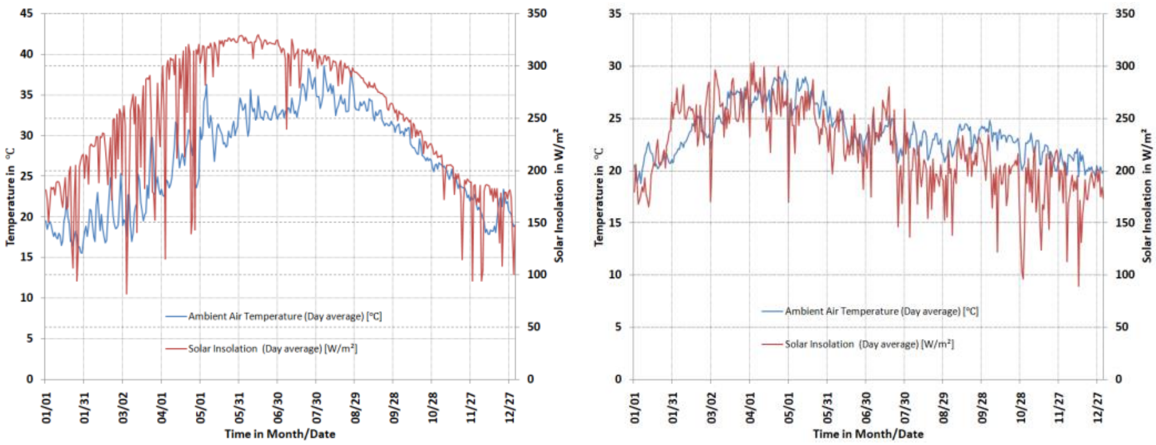
The main objective of the present work is to analyze the effect of use of PCM as an outer layer for the sidewalls. As this would be a one-time investment it is important to look into the effects throughout the year and also during the months of extreme weather when the energy consumption can be maximum. This can be identified by analyzing the annual room air temperature variations.

The simulations were carried out for all the three weather conditions. The outer surface of the sidewalls were expected to reach a maximum temperature above 56°C in the hot arid / warm tropical regions in the afternoon hours [15, 16]. On the other hand, in the extreme cold regions like Finland, the wall outer surface temperature can be as low as -5°C to -30°C. As mentioned earlier, the rooms analyzed in the present work were assumed as class rooms (65 occupants) with working hours from 8am – 5pm. It is important to ensure better thermal comfort during the working hours. The model rooms were considered as *uncontrolled zones* and hence no heating/cooling set points were set in the present simulations. The months of summer and winter as observed in the considered three regions are tabulated in table 4. Hence, in the present work the PCM with different melting points which can cause latent heat absorption during the working hours are chosen. The Pluss Pvt Ltd, Delhi, India has various PCM products [14] and is affordable. The thermo-physical properties of the PCM justified in the present work are referred from these products. The annual weather conditions for the three cities chosen are as shown in figure 2.

Region	**Months of Summer season**	**Months of Winter Season**	**Remarks**
Abu Dhabi	April - September	December - February	Summer is severe, cooling load is usually high.
Bangalore	March - June	December - February	Summer is bearable, cooling load is moderate.
Helsinki	June - September	November - March	Winter is severe. Heating load is usually high.

Table 4:

Months of summer and winter usually observed in the considered three climatic zones: Abu Dhabi, Bangalore and Helsinki.



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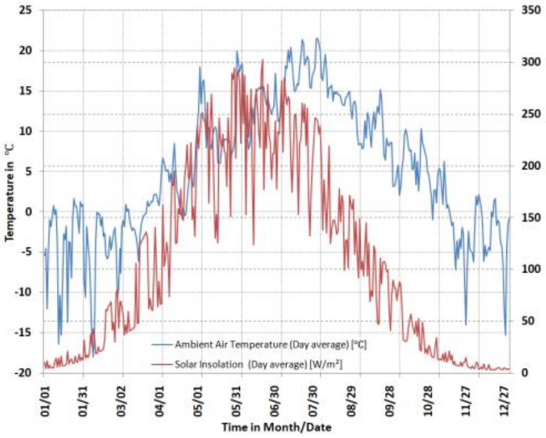


(c)

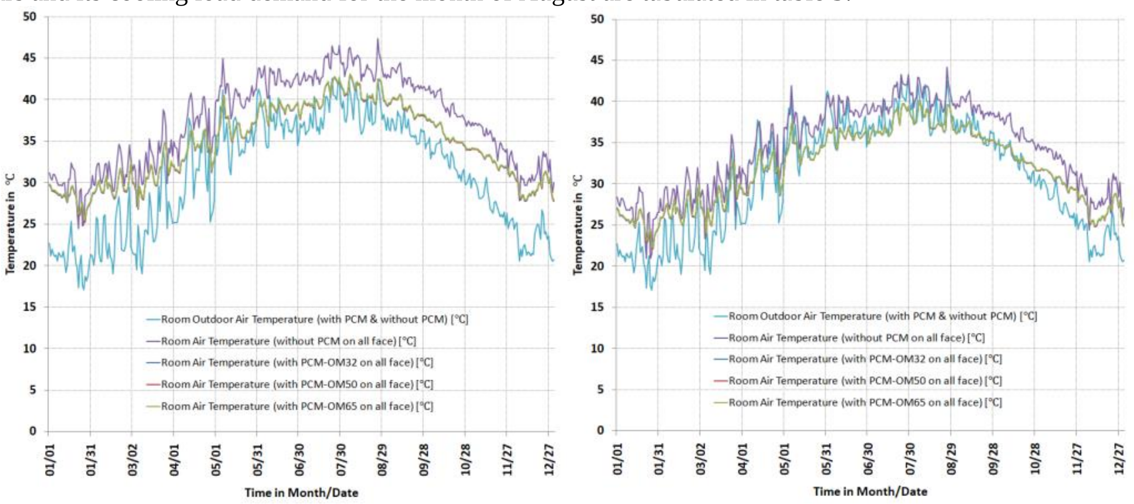
Figure 2:

Annual Solar radiation and ambient air temperature variations (a) Abu Dhabi, UAE, (b) Bangalore India, (c) Helsinki, Finland

In Abu Dhabi, the average air temperature goes as low as 15℃ in the months of January and February; highest average temperatures recorded are around 40℃ in the months of July and August. The yearly diurnal variation is around 25℃. Similarly in case of Bangalore, the lowest is around 20℃ from July till February end and the highest is around 30℃ from March till May end. The city is locally called "air conditioned city". The yearly diurnal variation is around 10℃. Helsinki has extreme cold weather. Lowest temperatures are close to -20℃ (less than 0℃ from January till March end) and highest temperatures are close to 20℃ (only for two months – July and August). The yearly diurnal variation is around 40℃ which is more than that for Abu Dhabi. Considering Solar radiation with the day average values for Abu Dhabi, maximum was observed during the months of April to August as shown in figure 2(a), for Bangalore the same is during the months of March to May as shown in figure 2(b). For Helsinki, it is below 50W/m^2 during October to March as shown in figure 2(c).

RESULTS AND DISCUSSIONS

Let us first consider the case of hot arid weather i.e., Abu Dhabi. Figure 2(a) shows the annual weather conditions at Abu Dhabi, UAE. The solar radiation goes to as high as 1050 W/m² and the ambient air temperature can be as high as 39°C during the month of August. In general, the weather is dry and hot throughout the year. The room air temperature variations are as shown in figure 3(a) – 3(c). The outer PCM layer was observed to lower the room air temperature throughout the year for all the three shapes – shallow, tall and cubical. The PCM considered for hot arid weather conditions were OM32, OM50 and OM65. However, the room temperature variations remained same for the different types of PCM considered. No significant effect on the time lag due to the different PCM was also observed. Among the shallow, tall and cubical shaped room cases, the lowest room air temperatures could be witnessed in the case of shallow room. The room air temperatures were not much different for tall and cubical shapes. These can be attributed to the ratio of wall surface area to inside air volume (WSA / IAV) which are tabulated in table 1. The outer surfaces of all the sidewalls of the rooms were the outer surfaces of the PCM layer. These outer surfaces were subjected to solar radiation and the ambient air during the day time. The solar gain in the case of shallow room was lowest due to the lowest ratio of WSA / IAV. The convection heat losses from the outer surface were relatively less significant. The room temperatures were observed to be maximum during the month of August. The improvement in the energy efficiency due to PCM can be studied by comparing the amount of heat to be removed from or added to the room air to maintain the room air at 25°C. The room air can be considered as lumped mass in the present study as no ventilation was considered. The average room air temperatures during the working hours and its cooling load demand for the month of August are tabulated in table 5.



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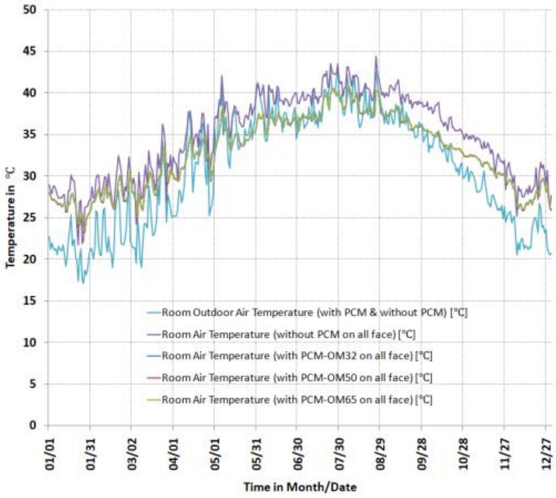


(c)

Figure 3:

Temperature in °C Vs Time in Month/Date (with PCM OM32, 50, 65 on all face & without PCM on all face) for one year (Place-Abu Dhabi) – (a) Shallow case, (b) Tall case, (c) Cubic case

Description	**Outdoor air temp. average for working hours 8AM-5PM (°C)**	**Room inside air temp. average for working hours 8AM-5PM (°C)**		**Cooling load to maintain 25°C room temperature $Q_{wo,PCM}$ (kWh)**	**Cooling load to maintain 25°C room temperature $Q_{w,PCM}$ (kWh)**	**Percentage of reduction in cooling load with PCM (%)**
		without PCM $T_{wo,PCM}$	**with PCM $T_{w,PCM}$**			
Case 1 (shallow)	38.83	44.09	**OM32 = 40.88** OM50 = 40.94 OM65 = 41.02	6.38	**5.31** 5.33 5.36	**16.82** 16.50 16.08
Case 2 (tall)	38.83	40.70	**OM32 = 37.81** OM50 = 37.84 OM65 = 37.87	5.25	**4.28** 4.29 4.30	**18.41** 18.22 18.03
Case 3 (cubic)	38.83	40.98	**OM32 = 38.58** OM50 = 38.63 OM65 = 38.67	5.34	**4.54** 4.56 4.57	**15.02** 14.71 14.46

Table 5:

Room average temperature and cooling load for Abu Dhabi (summer period - August month)

The table also depicts the percentage reduction in the cooling load under the lumped air mass assumption. This simple calculation was done using Equation 1 which represents the percentage of reduction in sensible cooling load. The total cooling load and sensible cooling load are identical in the present work as no ventilation and no internal moisture sources are considered. Hence, equation 1 gives the intended values.

$$Percentage\ of\ reduction\ in\ cooling\ load\ with\ PCM = \frac{\{mC_p(T_{wo,PCM}-25)\}-\{mC_p(T_{w,PCM}-25)\}}{mC_p(T_{wo,PCM}-25)}$$ ……..………… …… (1)

Where,

m - mass of the enclosed air in kg

C_p – specific heat capacity in kJ/kg°C

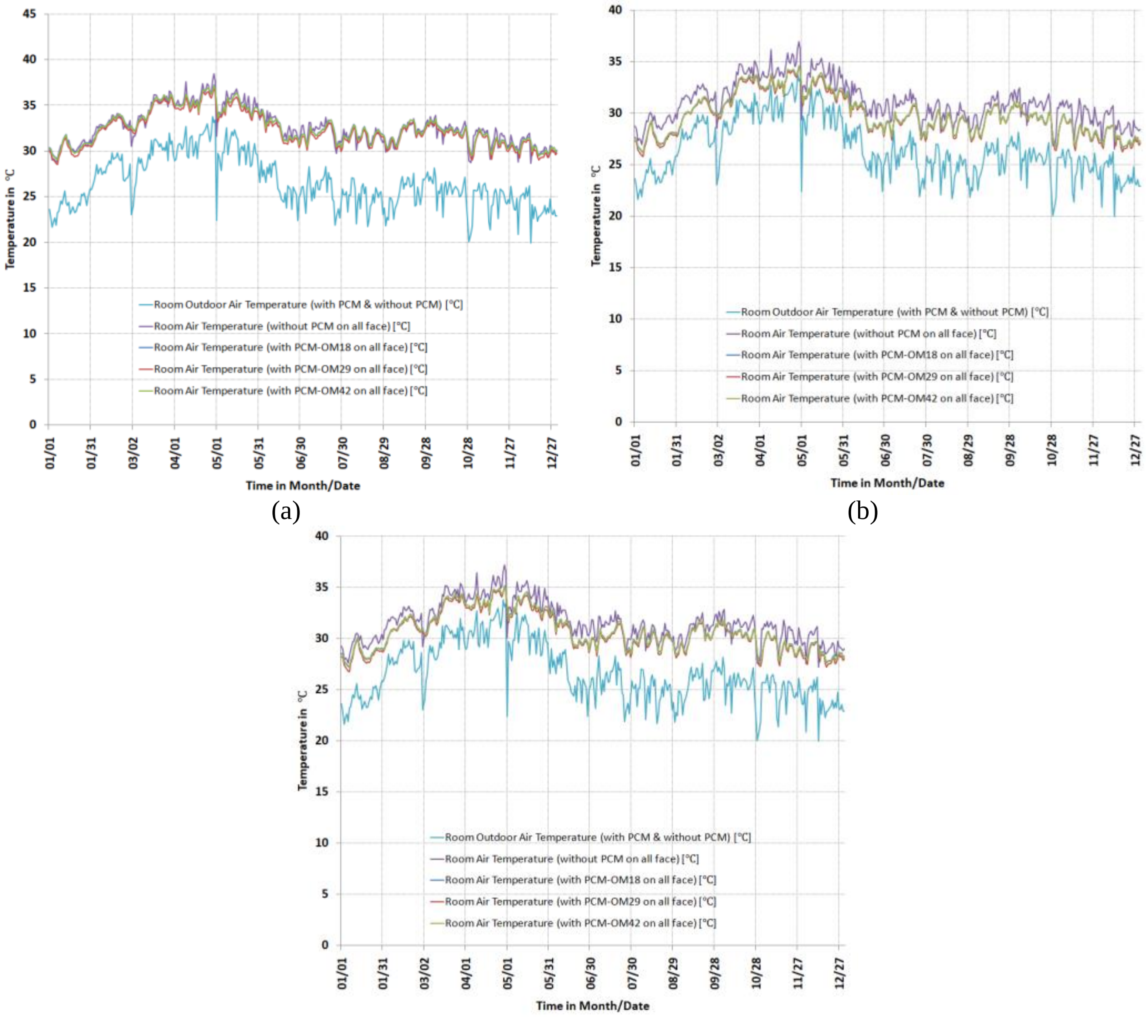
product m*C_p is the thermal mass of the enclosed air

$T_{wo,PCM}$ – room inside air temperature without PCM in °C

$T_{w,PCM}$ – room inside air temperature with PCM in °C

Around 18.41% reduction in the cooling load with outer PCM layer during the working hours for the August month can be achieved for the tall room case. Similarly, the reduction in the cooling load in the case of shallow and cubical rooms can be 16.82% and 15.02% respectively. The percentage reduction is almost similar for any of the considered PCM i.e., OM32, OM50 and OM65. On the other hand, the shallow room was observed to attain relatively higher room air temperatures with or without PCM. Therefore the shallow rooms would demand relatively higher cooling as compared to either tall or cubical shaped rooms.

Now, let us consider the case of warm tropical region - Bangalore, India. Though the Bangalore weather is considerably moderate as compared to the case of Abu Dhabi the use of PCM can still be useful. Figures 4(a) – 4(c) show the average (during working hours only) room air temperature throughout the year with and without PCM for the shallow, tall and cubical shaped rooms. The PCM assumed for the Bangalore weather were OM18, OM29 and OM42. Considerable decrease in average room temperatures was observed with PCM as shown in the figure 4(a) – 4(c). Negligible differences due to different PCM were observed except that OM29 resulting in slightly lower temperature than the other two. On the other hand, significant time lag of around 1.5 to 2 hours was observed in the diurnal room air temperature variations with PCM as compared to that without PCM. Similar to Abu Dhabi case, the shallow room was found to be relatively at higher temperature than the tall and cubic shaped rooms. The percentage reduction in cooling load is depicted in table 6. It was found that the PCM layer for shallow room can reduce the cooling load by 6.24%. In the case of tall and cubic shaped rooms, the reduction is around 15.19% and 11.99% respectively which are relatively insignificant.



(a) (b)

(c)

Figure 4

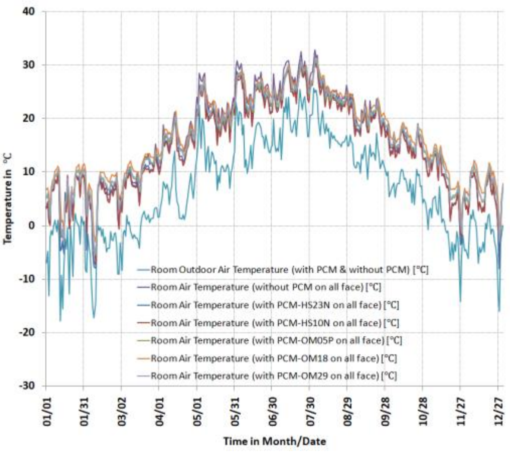
Temperature in °C Vs Time in Month/Date (with PCM OM18, 29, 42 on all face & without PCM on all face) for one year (Place-Bangalore) – (a) Shallow case, (b) Tall case, (c) Cubic case

Description	Outdoor air temp. average for working hours 8AM-5PM (°C)	Room inside air temp. average for working hours 8AM-5PM (°C)		Cooling load to maintain 25°C room temperature $Q_{wo,PCM}$ (kWh)	Cooling load to maintain 25°C room temperature $Q_{w,PCM}$ (kWh)	Percentage of reduction in cooling load with PCM (%)
		without PCM $T_{wo,PCM}$	with PCM $T_{w,PCM}$			
Case 1 (shallow)	31.18	36.06	OM18 = 35.74 **OM29 = 35.37** OM42 = 35.71	3.70	3.59 **3.47** 3.58	2.89 **6.24** 3.16
Case 2 (tall)	31.18	34.48	OM18 = 33.22 **OM29 = 33.04** OM42 = 33.20	3.17	2.75 **2.69** 2.74	13.29 **15.19** 13.50
Case 3 (cubic)	31.18	34.84	OM18 = 33.87 **OM29 = 33.66** OM42 = 33.86	3.29	2.97 **2.90** 2.96	9.86 **11.99** 9.96

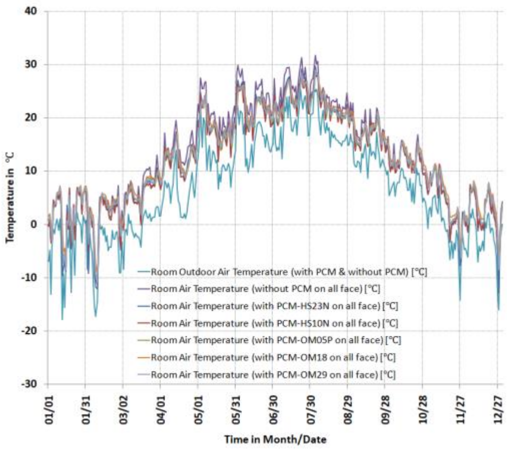
Table 6

Room average temperature and cooling load for Bangalore (summer period - April month)

The case of Helsinki, Finland is different from the hot arid / warm tropic weather conditions with very low solar insolation and sub-zero temperatures during most of the days of the year as shown in the figure 5(a) – 5(c). Similar simulations were carried out but with a different set of PCM as the weather is different demanding heating of the room. Initially HS23N, HS10N and OM05P were assumed. From the analysis it was learned that the room air could be maintained at warmer temperatures by using PCM with a bit higher melting points. Hence OM18 and OM29 were also assumed for simulations. It was observed that the heating load can be the least with OM18 and the details are tabulated in table 7. The study suggests that OM18 can be a suitable PCM as an outer layer in such extreme cold climatic regions. However, the analysis of reduction in heating load during each month seems to provide some additional useful information which are tabulated in table 8.



(a)



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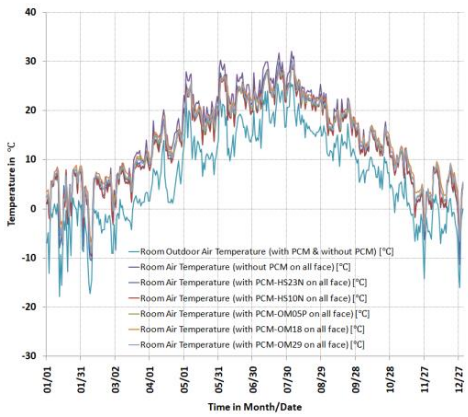


(c)

Figure 5

Temperature in °C Vs Time in Month/Date (with PCM HS23N, HS10N, OM05P, 18, 29 on all face & without PCM on all face) for one year (Place-Finland Helsinki) – (a) Shallow case, (b) Tall case, (c) Cubic case

Description	Outdoor air temp. average for working hours 8AM-5PM (°C)	Room inside air temp. average for working hours 8AM-5PM (°C)		Heating load to maintain 25°C room temperature $Q_{wo,PCM}$ (kWh)	Heating load to maintain 25°C room temperature $Q_{w,PCM}$ (kWh)	Percentage of reduction in heating load with PCM (%)
		without PCM $T_{wo,PCM}$	with PCM $T_{w,PCM}$			
Case 1 (shallow)	-5.08	4.52	HS23N = 3.92 HS10N = 4.03 OM05P = 5.58 **OM18 = 7.09** OM29 = 5.81	6.85	7.05 7.01 6.50 **5.99** 6.42	-2.93 -2.39 5.18 **12.55** 6.30
Case 2 (tall)	-5.08	1.25	HS23N = 0.52 HS10N = 0.64 OM05P = 1.39 **OM18 = 2.23** OM29 = 1.47	7.94	8.19 8.15 7.90 **7.62** 7.87	-3.07 -2.57 0.59 **4.13** 0.93
Case 3 (cubic)	-5.08	2.52	HS23N = 1.83 HS10N = 1.95 OM05P = 2.95 **OM18 = 4.01** OM29 = 3.08	7.52	7.75 7.71 7.37 **7.02** 7.33	-3.07 -2.54 1.91 **6.63** 2.49

Table 7
Room average temperature and heating load for Finland-Helsinki (Winter period - February month)

Month	Shallow case			Tall case			Cubic case		
	Heating load $Q_{wo,PCM}$ (kWh)	Heating load $Q_{w,PCM}$ (kWh)	Percentage of reduction in heating load with PCM (%)	Heating load $Q_{wo,PCM}$ (kWh)	Heating load $Q_{w,PCM}$ (kWh)	Percentage of reduction in heating load with PCM (%)	Heating load $Q_{wo,PCM}$ (kWh)	Heating load $Q_{w,PCM}$ (kWh)	Percentage of reduction in heating load with PCM (%)
Jan	6.74	5.92	12.16	7.86	7.50	4.53	7.43	6.93	6.78
Feb	6.85	5.99	12.55	7.94	7.62	4.12	7.52	7.02	6.62
Mar	5.02	4.64	7.49	5.98	6.16	-2.93	5.60	5.60	-0.03
Apr	2.91	2.74	5.92	3.73	4.15	-11.43	3.40	3.63	-6.77
May	0.87	0.86	0.26	1.54	2.12	-37.94	1.28	1.66	-30.37
Jun	0.28	0.24	14.72	0.32	0.87	-172.09	0.09	0.47	-400.95
Jul	0.91	0.75	17.44	0.36	0.30	16.99	0.56	0.07	87.11
Aug	0.28	0.40	-41.35	0.35	0.65	-88.31	0.11	0.28	-150.13
Sep	1.56	1.19	23.81	2.35	2.45	-4.28	2.04	1.98	2.84
Oct	3.31	2.73	17.46	4.22	4.08	3.32	3.87	3.59	7.21
Nov	5.88	4.99	15.14	7.00	6.55	6.44	6.58	5.99	9.01
Dec	6.65	5.74	13.64	7.80	7.31	6.34	7.37	6.74	8.54

Table 8:
Heating load for Finland-Helsinki (for one year)

It was observed that for around 5 months from May till August the heating load without PCM is less than 1kWh for all the three cases: shallow, tall and cubic shaped rooms. The reduction in heating load with PCM during the working hours during most of these five months were observed to be negative. That is, excess heat is getting accumulated inside the room due to PCM. Among the remaining 7 months, the maximum reduction in heating was found to be 13.64% (December), 6.34% (December) and 9.01% (November) for shallow, tall and cubic shaped rooms respectively. This study suggests that having no PCM layer during May to August could result in negligible heating / cooling load during those 5 months. Similar observations are reported in Airaksinen et al. [17] in which the authors did analyze the power demand for space heating for a house in Helsinki climatic zone. They have shown that the heating load is almost zero from the month of May till September.

Comparison of heating load demand with PCM for shallow, tall and cubic cases for Helsinki location is shown in figure 6 and as that of cooling load demand with PCM for Abu Dhabi is shown in figure 7(a) and for Bangalore is shown in figure 7(b).

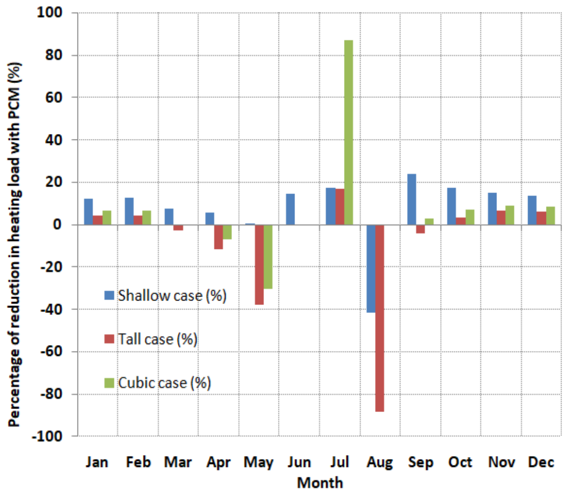
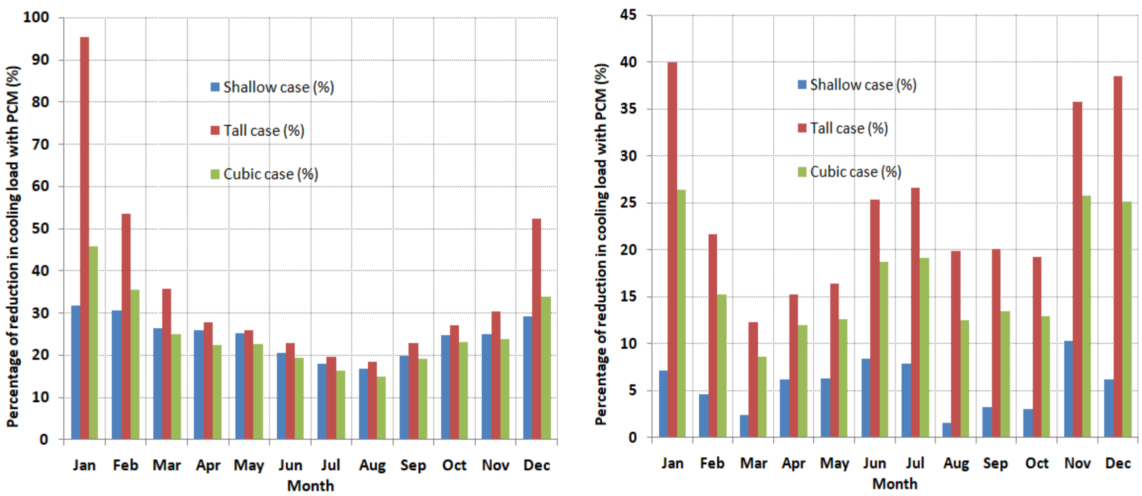


Figure 6:
Percentage of reduction of heating load with PCM for Finland-Helsinki (for one year)



(a) (b)

Figure 7:
Percentage of reduction of cooling load with PCM (for one year)
(a) Abu Dhabi (b) Bangalore

CONCLUSIONS

Use of PCM as an outer layer for the sidewalls of a room (or a building in general) can be useful in the three different climatic regions: hot arid, warm-tropical and extreme cold. The commercially available PCM with melting points in the range of 32°C to 65°C can result in same room air temperatures in the hot-arid regions like Abu Dhabi. On the other hand, tall room was observed to demand lowest cooling requirement. However, the percentage of reduction in cooling load is around 16.82% and 18.41% for shallow and tall rooms during the month of August. For cubic shaped room the same is around 15.02%. Similar trend was observed throughout the year also.

PCM as an outer layer for the sidewalls can be useful in warm tropical regions like Bangalore, India but would not be as effective as that in hot-arid regions. The reduction in cooling load due to PCM was observed to be around 15.19% for tall room followed by 11.99% and 6.24% for cubic and shallow rooms respectively during the month of April. The trend remains same for the whole year.

In the extreme cold climatic regions, the PCM as an outer layer for the sidewalls seems to be useful partially during a few months of the year. PCM with 18°C as melting point seemed to a suitable PCM. The analysis of heating loads with and without PCM and the percentage of reduction in heating load has shown that the PCM is not needed for around 5 months of the year i.e., from May till August end. Otherwise, the heat accumulation can cause the cooling load. Hence one may prefer to have movable / removable PCM layer so that it can be removed temporarily whenever necessary. Around 5% to 10% reduction in heating load during the other 7 months with PCM is possible.

REFERENCES

[1] Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. *Renewable and sustainable energy reviews*, *15*(8), 3617-3631. https://doi.org/10.1016/j.rser.2011.07.014.

[2] Kuznik, F., & Virgone, J. (2009). Experimental assessment of a phase change material for wall building use. *Applied energy*, *86*(10), 2038-2046. https://doi.org/10.1016/j.apenergy.2009.01.004.

[3] Kuznik, F., David, D., Johannes, K., & Roux, J. J. (2011). A review on phase change materials integrated in building walls. *Renewable and Sustainable Energy Reviews*, *15*(1), 379-391. https://doi.org/10.1016/j.rser.2010.08.019.

[4] Cui, Y., Xie, J., Liu, J., & Pan, S. (2015). Review of phase change materials integrated in building walls for energy saving. *Procedia Engineering*, *121*, 763-770. https://doi.org/10.1016/j.proeng.2015.09.027.

[5] Lee, K. O., Medina, M. A., Raith, E., & Sun, X. (2015). Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management. *Applied Energy*, *137*, 699-706. https://doi.org/10.1016/j.apenergy.2014.09.003.

[6] Wi, S., Chang, S. J., & Kim, S. (2020). Improvement of thermal inertia effect in buildings using shape stabilized PCM wallboard based on the enthalpy-temperature function. *Sustainable Cities and Society*, *56*, 102067. https://doi.org/10.1016/j.scs.2020.102067.

[7] Chwieduk, D. A. (2013). Dynamics of external wall structures with a PCM (phase change materials) in high latitude countries. *Energy*, *59*, 301-313. https://doi.org/10.1016/j.energy.2013.06.066.

[8] Childs, K. W., & Stovall, T. K. (2012). Use of phase change material in a building wall assembly: a case study of technical potential in two climates. International High Performance Buildings Conference. Paper 58. http://docs.lib.purdue.edu/ihpbc/58.

[9] Shi, X., Memon, S. A., Tang, W., Cui, H., & Xing, F. (2014). Experimental assessment of position of macro encapsulated phase change material in concrete walls on indoor temperatures and humidity levels. *Energy and buildings*, *71*, 80-87. https://doi.org/10.1016/j.enbuild.2013.12.001.

[10] Lei, J., Kumarasamy, K., Zingre, K. T., Yang, J., Wan, M. P., & Yang, E. H. (2017). Cool colored coating and phase change materials as complementary cooling strategies for building cooling load reduction in tropics. *Applied Energy*, *190*, 57-63. https://doi.org/10.1016/j.apenergy.2016.12.114.

[11] Arıcı, M., Bilgin, F., Nižetić, S., & Karabay, H. (2020). PCM integrated to external building walls: An optimization study on maximum activation of latent heat. *Applied Thermal Engineering*, *165*, 114560. https://doi.org/10.1016/j.applthermaleng.2019.114560.

[12] Sravani, K., Parameshwaran, R., & Ram, V. V. (2020). Experimental Study on PCM-Based External Wall Cladding for Energy Efficient Buildings. In *Recent Advances in Mechanical Engineering* (pp. 513-526). Springer, Singapore. https://doi.org/10.1007/978-981-15-1071-7_42.

[13] EnergyPlus. Weather Data. [Internet].2021 EnergyPlus. [cited 10 November 2021] from https://energyplus.net/weather.

[14] PLUSS – PCM Range [Internet]. Pluss.co.in. 2021 [cited 10 November 2021]. Available from: https://www.pluss.co.in/product-range-PCM.php.

[15] Karbor, R. G., & Mohamed, I. (2010). Development and Construction of Bioclimatic Double Skin Active Facade for Hot and Humid Climate of UAE. https://hdl.handle.net/1969.1/94076.

[16] Haggag, M. A., Elmasry, S. K., & Hassan, A. (2012). Design with nature: integrating green façades into sustainable buildings with reference to Abu Dhabi. *WIT Transactions on Ecology and the Environment*, *160*, 37-47.

[17] Airaksinen, M., & Vuolle, M. (2013). Heating energy and peak-power demand in a standard and low energy building. *Energies*, *6*(1), 235-250. https://doi.org/10.3390/en6010235.

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