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Energy Savings Potential of Phase Change Material Integrated Building Envelope in South Texas

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ABSTRACT

The performance of phase change material (PCM) integrated building envelope in terms of peak load reduction, peak load time delay and thermal demand improvement was investigated for a prototype detached single family house in a hot climate location. Five market available PCM layers, which can be easily inserted into traditional wall construction, were selected and coupled into different walls and different locations within the wall. Annual simulation results from EnergyPlus indicated the significant effect of PCM integrated envelope for the studied case. The PCM layer of melting temperature of 23 C is determined as the best one for south wall implementation. When it is placed to the interior of the insulation component of the wall, heat flux at heating load peak is reduced by 22.3% and heat flux at cooling load peak is reduced by 12.3%. For ceiling application, the best performing one is the PCM layer of melting temperature of 25 C and when it is placed below the insulation component of the ceiling. Reduction in peak heat flux is 30.2% for heating and 25.8% for cooling. The greater reduction in peak heat flux of ceiling than south wall is due to its larger area. For peak heat flux time delay, all PCM cases show similar effect of about 30 minutes for typical heating time and 60 minutes for typical cooling time. The performance of PCM layers in reducing annual thermal demand is not as evident as in heat flux: reduction in heating demand ranges from 7.9% to 54.34% and reduction in cooling demand ranges from 1.2% to 7.2%.

1. INTRODUCTION

The thermal properties of building envelope are critical with regard to building energy consumption and occupants' thermal comfort. As a result, different versions of standards and codes have been developed to guide the design of building envelope. For example, ASHRAE standards (2007) and International Energy Conservation Code (IECC) have published prescriptive criteria of thermal resistance for envelop elements including ceilings, walls, floors and fenestrations according to weather characteristics of different climate zones. Increased thermal resistance can reduce heat transfer between building inside and outside, and consequently decrease energy consumption. However, there is a tradeoff point beyond which additional increase in thermal resistance will instead result in higher energy consumption. To further reduce peak loads of building air-conditioning and save energy, phase change materials (PCMs) have been integrated into building envelope. PCMs are substances change phase at a certain temperature range with capabilities of storing and releasing large amounts of energy. Being an integrated component of envelope, they absorb heat when outdoor temperature rises and solar energy strikes the building until complete phase change occurred. When surrounding temperature is lower than their phase-change temperature, heat will then flow out of PCMs and reverse phase change occurs. Previous researches have shown that PCMs integrated building envelope can mitigate indoor air temperature swings, decrease cooling loads and greatly reduce or shift the building peak loads (Zhu et al., 2009; Gracia and Cabeza, 2015).

Halford and Boehm (2007) simulated reductions in peak cooling load by 11-25% and 19-57% via installing encapsulated PCM within the ceiling or wall insulation when compared to envelopes of the same mass and of the same insulation but no phase change, respectively. Kondo and Ibamoto (2006) experimented the effects of the peak shaving control of air-conditioning systems using PCM ceiling board in an office building located in Tokyo. They reported that the maximum thermal load reduced to 85.2% of that of using rock wool ceiling board after adding microcapsulate PCM. But the integrated thermal load increased by 5.3%. Kissock et al. (1998 and 2006) investigated the thermal performance of phase change wallboard experimentally and numerically. They measured a reduction in indoor peak air temperature up to 10 °C comparing the PCM test cell with the conventional test cell (1.22 m × 1.22 m × 0.61 m). A finite difference numerical mode was developed and modified using their measured data. For the location of Dayton Ohio, the model simulated that the addition of PCM gypsum wallboard in frame walls reduced the peak and annual cooling loads through the wall by 16% and 9% respectively. The performance of PCM frame wall in reducing peak air-conditioning demand in residential buildings was studied by Zhang et al. (2005) with two test cells (1.83 m × 1.83 m × 1.22 m). Their experimental results showed that the retrofit test cell with a 10% PCM concentration reduced the peak heat flux through the wall and space cooling load by about 15% and 8.6% respectively, as compared with the control test cell. They also reported that the west and north walls achieved higher reductions in wall heat flux than the south wall and the load shifting was spread over many hours from about midnight until about 1 pm. Later the test cells were used again to access the integration of a thin PCM layer in a residential building wall for heat transfer reduction and management (2015). The PCM layer was installed at different locations within the wall cavities of south and west facing walls of the test cells to identify the optimal integration locations. They reported the maximum peak heat flux reduction of 51.3% for the south wall and 29.7% for the west wall when the PCM layers were at their respective optimal locations. Also, their test showed the maximum peak heat flux time delay of 6.3 hours and 2.3 hours for the two walls. Through hot box experiments, Cao et al. (2010) concluded that the attenuation effect of PCM layer on the mean air and interior surface temperatures was noticeable. The benefits of peak heat flux reduction and time delay can be reflected as reduced size of air-conditioning equipment, and improved system operation and efficiency.

In order to enable whole building dynamic simulation with PCM presents, several studies have been performed to develop or refine the PCM modeling procedure. EPS-r models the behavior of PCM with its special materials facility (Heim and Clarke, 2004; Heim, 2006). The effect of phase transition is expressed as a latent heat generation term based on effective heat capacity method adding to the energy balance equation. Ibanez et al. (2005) presented a simple methodology for the energetic simulation of buildings with PCM components in TRNSYS (Type 56). The PCM model in EnergyPlus was verified and validated using a similar approach as dictated by ASHRAE Standard 140 (2007) consisting of analytical verification, comparative testing and empirical validation (Tabares-Velasco et al., 2012). This valuable work identified and fixed two bugs in the program and enabled validated and reliable simulations to be delivered by versions beyond 7.1, along with its outstanding strengths in whole building dynamic modeling. Besides, the program was also tested before by an additional set of eight cases, a combination of analytical cases and numerical cases, in Tabares-Velasco and Griffith (2012). Based on these work, researchers should feel confident about using EnergyPlus in studies involving PCM components.

Despite the researches reviewed above, the studies on energy performance of buildings using PCMs are still insufficient. The effectiveness of PCM components in envelope is strongly influenced by several factors including climate, building characteristics, PCM integration location in the wall, PCM phase changing temperatures, application wall orientation, and etc. Texas is a highly populated and energy-intensive state with long and hot summer. Residential buildings in the area typically have light construction and present low energy efficiency. Therefore, a comprehensive study of PCMs integrated residential building envelope is needed. In this paper, five market available PCM layers are coupled into the walls and ceiling of a prototype detached single-family house in San Antonio, Texas. Annual simulations are performed using EnergyPlus to evaluate the improvements of peak load and thermal demand of cases with PCM layers at different locations in the space surfaces over the no PCM case. Peak load time delay and free-floating uncomfortable indoor air temperature mitigation are also investigated for representative cases with optimal PCM layer at optimal location.

2. PCM MODELING IN ENERGYPLUS

The titles of the main sections have to be centered, numbered and in 12-point bold type capital letters. With the exception of the abstract, nomenclature, references, and acknowledgements section headings have to be numbered. Blank lines need to be placed above and below each main section title. To model building envelope with PCM components in EnergyPlus, the conduction finite difference (CondFD) solution algorithm should be employed. The algorithm assumes one-dimensional energy flow through envelope construction and discretizes all elements into thermal nodes depending on the thermal diffusivity of the material and simulation time step (EnergyPlus, 2016). There are two options of implicit finite difference scheme for the ConFD algorithm, and the fully implicit scheme is used in this study. Heat balance of an internal thermal node (such as one of the PCM layer nodes) for the fully implicit scheme is expressed in equation (1) (EnergyPlus, 2016; Tabares-Velasco et al., 2012).

$$c_p \rho \triangle x \frac{T_i^{j+1} - T_i^j}{\triangle t} = k_W \frac{\left(T_{i+1}^{j+1} - T_i^{j+1}\right)}{\triangle x} + k_E \frac{\left(T_{i-1}^{j+1} - T_i^{j+1}\right)}{\triangle x} \tag{1}$$

In equation (1), k_W is thermal conductivity for interface between the i^{th} node and the $(i+1)^{th}$ node; k_E is the thermal conductivity for interface between the i^{th} node and the $(i-1)^{th}$ node. They are calculated as the average of the conductivities of the two materials at the interface. T is temperature; i is the node being modeled; $i+1$ is the adjacent node to the interior; $i-1$ is the adjacent node to the exterior; $j+1$ is the new time step; $j-1$ is the previous time step; Δt is time step; Δx is the finite difference layer thickness; ρ is density of material and c_p is specific heat of material.

For PCMs c_p is varying depending on the state of the material, so equivalent specific heat (equation (2)) obtained from the enthalpy-temperature function is used and updated at each time step in equation (1).

$$c_p^*\left(T\right) = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \tag{2}$$

where, h is enthalpy which is also a function of T.
The verification and validation studies indicated that time steps equal to or shorter than three minutes should be used in EnergyPlus for PCM modeling for accuracy concern. So in this study, time step is set to three minutes in the following simulations.

3. STUDIED PCM LAYERS

PCMs integration in building envelope has several different methods and they were all studied in existing literature. For example, imbibing, macro-encapsulation, direct mixing (of PCM with blown-in insulation). A relatively new integration method studied (Jin et al., 2013) is to encapsulate PCM in thin sealed polymer pouches, arrange in sheets laminated with aluminum foil on both sides and perforated around the PCM pouches. Similar products of this type are available from market with different and customable thickness, various densities, melting temperatures and specific heats. In this paper, five PCM layers, which can be easily inserted into traditional wall construction, are investigated. They share some common properties: a moderate thickness of 0.0208 *m*, thermal conductivity of 0.2 *W/m·K*, specific heat of 1970 *J/kg·K*, and density of 235 kg/m^3. Differences among them lie in the enthalpy-temperature function shown in Figure 1 and melting temperature. PCM1 melts around 21 °C as can be seen from Figure 1, or in other words, 21 °C is the peak melting temperature of PCM1. The peak melting temperatures of the other four PCM layers are 23 °C for PCM2, 25 °C for PCM3, 27 °C for PCM4 and 29 °C for PCM5.

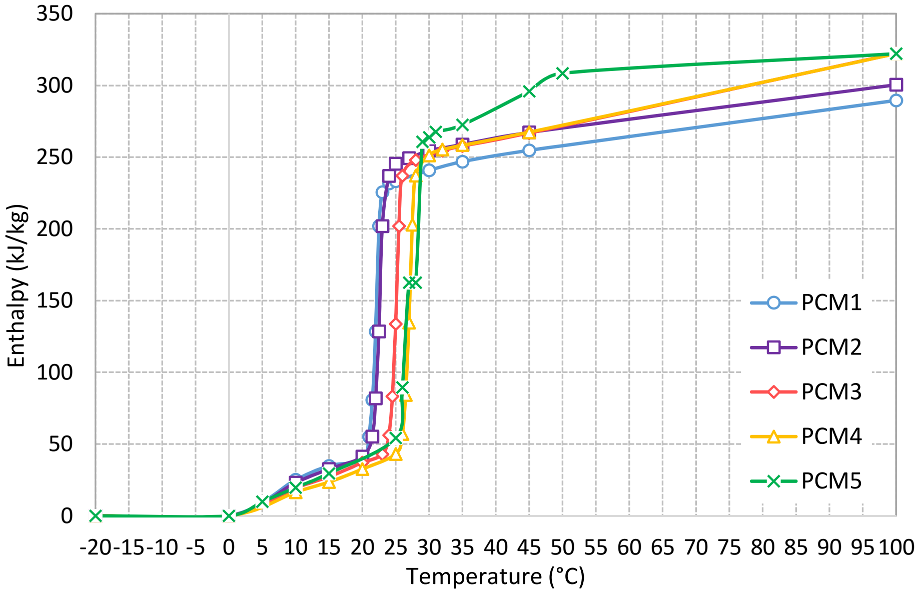

Figure 1: Variation of enthalpy as a function of temperature for the five investigated PCM layers

4. PROTOTYPE SINGLE-FAMILY HOUSE IN SAN ANTONIO TEXAS

The city of San Antonio is selected as a representative of the south Texas area in the study. It features a hot and long summer, comfortably warm or mild winter with a dozen subfreezing nights. Its weather information including monthly total solar energy incident on horizontal surface, monthly average outdoor air temperature and monthly average diurnal temperature range is illustrated in Figure 2. It's worth noticing that the diurnal temperature range is varying around 11 °C with a maximum of 25 °C and a minimum of 1.6 °C throughout the year.

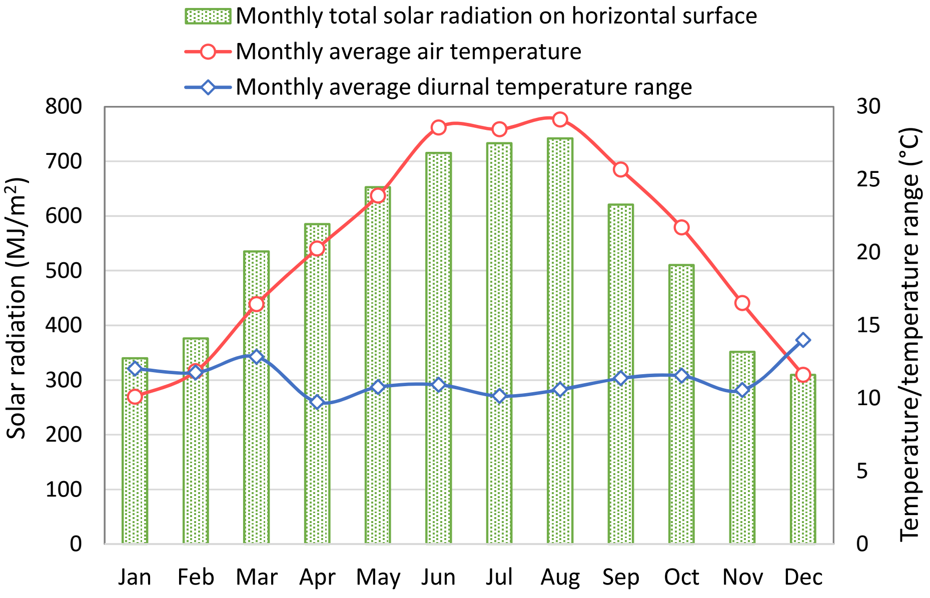

Figure 2: Weather information of the studied location (San Antonio, Texas)

A prototype of detached single-family house for this area is shown in Figure 3. It's from EnergyPlus example file consisting of three zones: the air-conditioned living zone, and the unconditioned attic zone and garage zone. The floor area of the three zones are 185 m^2, 228 m^2, and 42 m^2, respectively. There is one window on each wall, occupying

27% of the north wall, 17% of the south wall, and 26% of the east wall and west wall. Heating and cooling are always available for the living zone throughout the year with temperature setpoint changing with seasons: from Apr 1 to Oct 31, setpoints are 24 °C for cooling and 18 °C for heating; for the rest of the year, setpoints are 26 °C for cooling and 20 °C for heating.

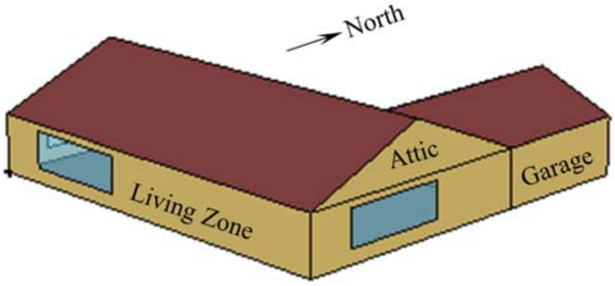

Figure 3: 3D view of the studied single-family house

For this type of residential house in the studied area, IECC (2006) and ASHRAE Standard 90.2 (2007) require thermal resistances of the ceiling (with attic space) and exterior walls to be R-30 and R-15. The Pacific Northwest National Laboratory (PNNL) have developed constructions satisfying this requirement and are adopted in this study. Details of the ceiling, roof and exterior wall constructions are listed in Table 1. Please refer to the residential prototype building models developed by PNNL for detailed construction of each envelope element.

Table 1: Construction details of the studied house

	Exterior wall (living zone)		**Ceiling (living zone)**
Outside layer	Stucco_1in	Outside layer	Ceil_consol_layer: 0.266 m
Layer 2	Bldg_paper_felt	Layer 2	Drywall_1/2in
Layer 3	Sheathing_consol_layer		
Layer 4	OSB_5/8in		**Roof**
Layer 5	Wall_consol_layer: 0.0889 m	Outside layer	Asphalt_shingle
Layer 6	Drywall_1/2in	Layer 2	OSB_1/2in

The ‘Wall_consol_layer’ of exterior wall and ‘Ceil_consol_layer’ of ceiling are selected as potential locations to insert the PCM layer and their thicknesses are indicated in Table 1 as well. Depending on thickness and thermal properties, 3 locations are investigated for exterior wall: PCM layer is placed to the exterior, at the middle and to the interior of ‘Wall_consol_layer’. Similarly, 5 locations are investigated for ceiling: PCM layer is placed above, at the depth of ¼, ½ and ¾ of the thickness of ‘Ceil_consol_layer’ within and below the ‘Ceil_consol_layer’. Note that complete schedules and internal heat gains for typical single-family houses follow the same settings from PNNL models.

5. RESULTS AND DISCUSSION

5.1 No PCM Integration Case

Load simulation is first performed for the original design of the house without PCM. Annual thermal demands per floor area, peak loads, corresponding heat flux through walls at load peaks and annual peak heat flux through walls for heating time and cooling time are summarized in the first row of Table 2 and Table 3. Cooling is dominating in San Antonio. The annual cooling demand is 63.01 kWh/m^2·year while the annual heating demand is only 5.32 kWh/m^2·year. Peak cooling load almost doubles peak heating load, and they are 6545.97 W and 3361.69 W respectively. It is also illustrated that the heat transfer through south wall is more intense than that of ceiling. With three minutes as the simulation time step, there are 949.4 hours during the year that the air-conditioning system is in heating mode. The corresponding number of hours for cooling is 5538.8 (also listed in Table 2 and Table 3). Because heating and cooling are always available, it is simulated that there are 105 days with heating needs and 323 days with cooling needs, indicating 63 days of both heating and cooling requirements within one day.

5.2 PCM Integrated Into South Wall

In total, 15 cases are simulated for integrating PCM layer into the south wall of living zone, combining the 5 samples of PCM layer and three integration locations in the wall. Simulation results are listed in Table 2. The influence of PCM layer on heating demand is significant with reductions ranging from 7.9% to 20.4% comparing with the case without PCM. However, the influence on cooling demand is minimal ranging from 1.2% to 2.9%. The third main column shows small decrease in peak thermal loads, about 0.6% ~ 3.7% for heating and 0.9% ~ 6.6% for cooling. It can be seen from the fourth and fifth main columns that heat transfer through the south wall is greatly decreased at both heating time and cooling time. The range of reduction in heat flux through wall at load peaks is from 8.3% to 52.7% during heating time and from 12.2% to 130% during cooling time. Reductions of annual peak heat flux through the south wall show similar trend. It may seem confusing that the PCM layers reduce heat flux through wall significantly but only result in minimal reduction in cooling demand. This can be explained by looking at the last main column of Table 2 and considering the inadequate area of south wall (42.04 m^2). For the studied amount of PCM in south wall, it benefits by decreasing heat transfer through the implementation wall, but also harms by shifting heat transfer to a later time which results in longer time with cooling requirement. Like the south wall integration cases here, the benefits are not superior greatly to penalties, so PCM integration presents great reduction in heat transfer but minimal decrease in annual cooling demand. If the amount of PCM increases, for example by using thicker layers or applying on larger wall area, the reduction in thermal demands could be more notable.

Use annual thermal demands as criterion, the best integration location (highlighted in Table 2) shows itself as inside the 'Wall_consol_layer' for all studied PCM layers. Comparing the PCM layers with each other, PCM2 is the best performing considering thermal demands and typical system efficiency.

Besides of heat flux decrease, another very important effect of PCM is peak time delay. To show this effect clearly, the days of monthly peak heating load and monthly peak cooling load for the case without PCM are identified and peak heat flux times of best-performing case are shown for these days. It is found that, on average the peak heat flux time is about 30 minutes for heating and 60 minutes for cooling later than the corresponding peak heat flux time of no PCM case.

Table 2: Summary of annual simulation results for all studied cases with PCM integrated into south wall

Cases	**Thermal demand ($kWh/m^2 \cdot year$)**		**Peak load (W)**		**Heat flux through south wall at load peaks (w/m^2)**		**Peak heat flux through south wall (W/m^2)**		**Total number of hours with**	
	Heating	*Cooling*	*Heating*	*Cooling*	*Heating*	*Cooling*	*Heating*	*Cooling*	*Heating*	*Cooling*
NoPCM	5.32	63.01	3361.69	6545.97	-11.88	11.89	-13.14	17.23	949.4	5538.8
PCM1S1	4.85	62.27	3337.22	6486.86	-10.39	10.38	-11.87	15.48	907.2	5560.3
PCM1S2	4.69	62.06	3238.07	6460.40	-5.62	9.66	-11.04	14.98	897	5554.4
PCM1S3	4.24	61.63	3271.79	6487.63	-7.76	10.44	-11.78	16.02	846.3	5505.1
PCM2S1	4.85	62.23	3338.06	6485.79	-10.49	10.34	-11.94	15.46	905.7	5568.1
PCM2S2	4.69	61.99	3269.17	6459.10	-6.51	9.61	-11.05	14.97	895.3	5567.1
PCM2S3	4.23	61.45	3326.5	6486.8	-9.23	10.42	-12.11	16.02	838.4	5536.3
PCM3S1	4.87	62.18	3340.31	6477.86	-10.72	10.1	-12.11	15.23	904.05	5590.4
PCM3S2	4.74	61.93	3332.65	6440.9	-9.36	9.11	-11.68	14.64	892.6	5591.75
PCM3S3	4.5	61.26	3340.6	6398.6	-10.88	8.91	-12.61	15.82	839.35	5631.15
PCM4S1	4.9	62.16	3340.96	6455.83	-10.78	9.53	-12.15	14.7	904.2	5599.3
PCM4S2	4.83	61.96	3338.07	6365.09	-10.44	7.13	-11.92	12.53	896.25	5605.7
PCM4S3	4.83	61.67	3341.04	6116.69	-10.9	-3.56	-12.62	10.45	876.2	5627.65
PCM5S1	4.89	62.15	3340.76	6433.85	-10.76	8.93	-12.14	14.22	903.25	5603.2
PCM5S2	4.8	61.93	3337.62	6296	-10.4	4.73	-11.9	11.87	894.6	5609.85
PCM5S3	4.76	61.55	3340.47	6125.15	-10.8	-1.71	-12.63	10.02	866.35	5637.25

Note: PCM1S1 indicates the case when PCM1 is integrated into the south wall at the first integration location (to the outside of 'Wall_consol_layer').

5.3 PCM Integrated Into Ceiling

For PCM integration into ceiling, 25 cases are simulated and results are shown in Table 3. Comparing with south wall integration cases, the influences of PCM layer on both heating demand and cooling demand are more evident. Reductions range from 10.9% to 54.3% for heating and 2.6% to 7.2% for cooling comparing with the case without

PCM. This is because the area of ceiling is larger than the area of south wall. Likewise, annual peak loads are smaller by 0.8%~14.9% for heating and 2.3%~21.1% for cooling respectively. If we look at the changes in heat flux through ceiling, reductions are smaller than the south wall cases. Heat flux from ceiling at load peaks are reduced by 5%~45% for heating and 6.3%~76.1% for cooling. For annual peak heat flux through ceiling, more complex trend presents. They are reduced for most of the studied cases, but with one or two cases increased. Similar to the south wall integration cases, the time with heating requirement is shorter for all cases while the time with cooling requirement could be longer or shorter.

The best-performing case of each PCM layer sample could be different depending on the criterion. Based on the annual thermal demand, case PCM3C5 is the best one. With the third PCM layer sample integrated into the fifth location in ceiling, peak heat flux time delay is about 30 minutes for heating and 60 minutes for cooling.

Table 3: Summary of annual simulation results for all studied cases with PCM integrated into ceiling

Cases	**Thermal demand ($kWh/m^2\cdot year$)**		**Peak load (W)**		**Heat flux through ceiling at load peaks (w/m^2)**		**Peak heat flux through ceiling (W/m^2)**		**Total number of hours with**	
	Heating	*Cooling*	*Heating*	*Cooling*	*Heating*	*Cooling*	*Heating*	*Cooling*	*Heating*	*Cooling*
NoPCM	5.32	63.01	3361.69	6545.97	-5.86	9.11	-7.69	9.97	949.4	5538.8
PCM1C1	4.52	61.4	3334.6	6396.9	-5.55	8.54	-7.23	10.25	845.4	5621.35
PCM1C2	4.22	60.99	3041.07	6119.55	-3.77	7.04	-6.51	9.38	827.65	5643.55
PCM1C3	4.04	60.78	3000.2	6039.2	-3.52	6.51	-6.3	8.89	813.2	5639.35
PCM1C4	3.66	60.52	2944.51	6094.03	-3.26	6.88	-6.54	9.22	797.7	5600.25
PCM1C5	2.43	59.51	2861.41	6340.36	-3.22	8.16	-7.21	10.24	523.8	5351.8
PCM2C1	4.54	61.35	3335.11	6390.93	-5.55	8.51	-7.25	10.23	845.35	5642.1
PCM2C2	4.25	60.93	3053.91	6115.03	-3.85	7	-6.6	9.34	829.7	5661.05
PCM2C3	4.1	60.72	3007.58	6035.84	-3.56	6.48	-6.37	8.86	816.1	5656.8
PCM2C4	3.74	60.4	2967.46	6088.43	-3.39	6.83	-6.63	9.18	791.95	5631.8
PCM2C5	2.58	59.01	2973.71	6336.16	-3.73	8.14	-7.64	10.22	522.75	5444.85
PCM3C1	4.66	61.29	3336.08	6365.01	-5.57	8.37	-7.29	10.14	856.9	5693.05
PCM3C2	4.43	60.88	3263.94	6090.75	-4.05	6.84	-6.76	9.2	841.75	5710.6
PCM3C3	4.32	60.64	3192.26	6007.08	-3.65	6.29	-6.54	8.7	827.35	5718.4
PCM3C4	4.15	60.27	3183.86	6017.52	-3.64	6.41	-6.79	8.86	802.5	5735.1
PCM3C5	3.68	58.48	3219.18	6013.45	-4.09	6.76	-7.84	9.42	684.3	5725.3
PCM4C1	4.74	61.29	3336.22	6324.82	-5.57	8.17	-7.3	10.02	867.35	5743.25
PCM4C2	4.53	60.92	3303.31	6046.39	-3.89	6.56	-6.77	8.98	857.05	5752.15
PCM4C3	4.45	60.74	3247.05	5941.09	-3.93	5.88	-6.54	8.36	852.5	5757.15
PCM4C4	4.35	60.45	3263.21	5797.76	-4.04	5.1	-6.79	7.9	839.2	5770.6
PCM4C5	4.24	58.68	3328.88	5542.65	-4.66	2.29	-7.84	6.69	798.8	5782.45
PCM5C1	4.72	61.27	3336.14	6300.2	-5.57	8.16	-7.3	9.98	865.6	5750.1
PCM5C2	4.49	60.87	3294.55	5977.31	-3.84	6.14	-6.75	8.65	852.15	5753.25
PCM5C3	4.38	60.67	3226.83	5875.95	-3.82	5.43	-6.5	7.96	846.7	5754.6
PCM5C4	4.25	60.36	3227.77	5656.61	-3.85	5.02	-6.71	7.57	832.5	5760.25
PCM5C5	4.08	59.29	3324.8	5166.12	-4.58	2.18	-7.9	6.83	778.6	5790.9

6. CONCLUSIONS

This paper investigated the performance of phase change material (PCM) integrated building envelope in terms of peak load reduction, peak load time delay and thermal demand improvement for a prototype detached single family house located in San Antonio, Texas. The thermal properties of the house envelope satisfy the prescriptive criteria of thermal resistance for ceiling, exterior wall, roof and etc, set by IECC 2016. Five market available PCM layers, which can be easily inserted into traditional wall construction, were selected and coupled into different walls and different locations within the wall. They share some common properties such as thickness, density and specific heat but with have different melting temperatures. Annual simulations were performed in EnergyPlus using 3 minutes as time step. The results indicated the significant effect of PCM integrated envelope for the studied case. The PCM layer of melting temperature of 23 °C is determined as the best one for south wall implementation. When it is placed to the interior of the insulation component of the wall, heat flux at heating load peak is reduced by 22.3% and heat flux at cooling load peak is reduced by 12.3%. For ceiling application, the best performing one is the PCM layer of melting temperature of 25 °C and when it is placed below the insulation component of the ceiling. Reduction in peak heat flux is 30.2% for heating and 25.8% for cooling. The greater reduction in peak heat flux of ceiling than south wall is due to its larger area. For peak heat flux time delay, all PCM cases show similar effect of about 30 minutes for typical heating time and 60 minutes for typical cooling time. The performance of PCM layers in reducing annual thermal demand is not as evident as in heat flux: reduction in heating demand ranges from 7.9% to 54.34% and reduction in cooling demand ranges from 1.2% to 7.2%. It is worth noticing that even though the reduction in thermal demand is small, the decreased load peaks still provide chances for energy saving because: i) air-conditioning system can operate at a later time with lower outdoor air temperature than it would without PCM during peak hours; and ii) lower outdoor air temperature implies better system efficiency (COP). Besides, the load profile is flatter. With a size reduced air-conditioning system, it enables the system to operate at relatively high cop range.

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