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Research Article

Application of Phase Change Material (PCM) for Cooling Load Reduction in Lightweight and Heavyweight Buildings: Case Study of a High Cooling Load Region of Iran

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A B S T R A C T

The application of phase change material (PCM) for energy conservation purposes in the residential buildings was investigated in the present study. Two types of building in terms of materials as the lightweight building (LWB) and heavyweight building (HWB) located in a high cooling load demanding region of Iran were considered for the study. Different types of PCM from organic and inorganic categories were examined to determine the most appropriate type of the buildings in terms of indoor air conditions and yearly required cooling load. The buildings in the existing form and with an added layer of PCM were simulated hourly, and indoor air conditions and yearly cooling loads were determined. EnergyPlus software was used for this purpose. The study revealed that the LWB with the added layer of calcium chloride hex hydrate (CCH) had the minimum yearly required cooling load with about 39.8 GJ, and 25.7 % reduction in the yearly cooling load was observed and the HWB had the best performance in terms of yearly required cooling load with the added n-eicosone (N.EIC) layer with about 28.8 GJ, which is a 47.1 % reduction in the yearly cooling load.After determining the proper PCM for the buildings, the recommended PCM was planned to be positioned in the external layer, mid-layer, and internal layer to examine the position effect on the yearly required cooling load.

1. INTRODUCTION

It has be predicted that that the world primary energy demand would increase by 36 % between 2008 and 2035, or 1.15 % per year on average [1,2]. In addition, for a period of 1998 and 2009, worldwide energy consumption showed more than 30 % increase [3]. According to the international energy agency, the greenhouse gas emission and energy consumption could be reduced by about 50 % by 2050, and the energy efficiency improvements could be very helpful in this issue [4].

Based on the statistics, the mean annul energy consumption growth rate in Iran is 4.6 % [5]. In addition, buildings are responsible for a considerable portion of the total energy consumption in countries with about 45 % [6]. It was also shown that, in buildings, the major energy consuming section involved the heating, ventilating, and air conditioning (HVAC) systems. Therefore, there is a great energy saving potential in building sector, and engineers try to implement modern energy saving technologies and new renewable energy sources to reduce energy consumption. One of the methods to achieve this objective is to develop thermal energy storage (TES) systems. By the application of TES systems, saving could be achieved, which consequently reduces the environment impact of energy use. In addition, these energy storage systems could address the mismatch between the supply and demand of energy.

Phase change materials (PCMs) have the potential of achieving this objective and are proposed to be implemented in the buildings constructions. By application of PCM it is expected to achieve improvements in the energy efficiency and indoor air quality of the buildings. The implementation of PCMs in buildings has been recommended as an operational way to reduce energy consumption in buildings [7,8].

PCMs are substances with relatively high latent heats of fusion. With a rise of temperature above the PCMs melting point, PCMs absorb heat and change the liquid phase at an almost constant temperature; in addition, with a decline of the temperature lower than the melting point, the PCMs release heat and turn to solid phase, again at an almost constant temperature [9]. A large number of PCMs with different melting points from almost -33 ^{o}C to 800 ^{o}C and different latent heats of fusion are available industrially [10].

Literature review indicates that the application of PCMs in buildings has been reported in some research studies [11-22]. For instance, Alawadhi [11] investigated the thermal behavior of building bricks containing PCMs in hot climates. In this research, a model consisting of bricks with cylindrical holes filled with PCMs was considered. For this purpose, a paramedic study was conducted to evaluate the effect of different design parameters, such as the PCM's quantity, type, and location in the brick. The study showed that the heat gain was considerably reduced by the application of PCM inside the bricks. It was also found that increasing the quantity of the PCM had a positive effect on the performance. In another research [12], the application of a latent heat TES cooling energy storage system was investigated for an office building in Santiago, Chile. In this study, a latent heat TES cooling energy storage based on ice was incorporated with a conventional chiller system of a commercial building. The study was conducted by EnergyPlus software. It was shown that the application of latent heat TES reduced the cooling energy consumption of the cooling system by 7.8 % for the studied period. The thermal performance of a building

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envelope with a ventilated facade with PCM in its air cavity was experimentally tested to study its capability in reducing the cooling load during the summer in the Continental Mediterranean climate [14]. The study revealed that the night free cooling effect of the system was an operational method to reduce the cooling load of the envelope.

Nelson et al. [15] studied the effect of incorporating PCM-wallboards in low-rise air-conditioned residential heavyweight buildings in Kuwait. For this purpose, an EnergyPlus single-zone model was considered; in addition, several window-to-wall ratios, different solar orientations, and some PCM-wallboard configurations were examined. It was reported that a 4-cm thick PCM-wallboard with a melting-peak temperature of 24 ^{o}C provided the lowest annual cooling demand across a variety of room orientations. It was also found that by the application of the PCM-wallboard an annual cooling energy savings of 4-5 % across all the case-studies could be achieved. In additions, in terms of yearly cooling demand and peak-loads, about 5-7 % reduction during summer months and 5-8 % in average daily cooling load were reported, respectively.

Solgi et al. [16] investigated a cooling load reduction in office buildings of hot-arid climates by means of PCMs and night purge ventilation. In this investigation, night purge ventilation as a passive technique for conserving cooling energy in the thermal mass of the building fabric was explored. To this end, PCMs with proper melting temperatures were applied to various building elements and to the whole model. The study showed that the application of PCMs considerably reduced the cooling load, except for the floor on the ground, increasing the load.

The application of PCMs in relocated lightweight buildings was investigated by Marina et al. [17]. In this research, the positive effect of PCMs on indoor thermal conditions of the buildings was revealed. In addition, the study showed that energy performance in the lightweight buildings (LWB) during both heating and cooling seasons in arid and warm temperatures could be improved by the application of PCMs. PCM in brick constructions as a solution for passive cooling was experimentally studied by Castell et al. [18]. To this end, several cubicles were fabricated, and their thermal performance was measured by the time. The study showed that the PCM could reduce the peak temperatures up to 18 ^{o}C and smooth out daily fluctuations. It was also found that, in summer 2008, about 15 % reduction in the electrical energy consumption was achieved in the PCM cubicles.

In another research, Guarino et al. [19] studied the performance of a building integrated with PCM to increase the energy performances of solaria in a cold climate. In this study, a wall opposing a highly glazed façade was employed as the thermal storage with PCM incorporated in the wall. The study was conducted both experimentally and numerically. It was indicated that, by the application of PCM, daily temperature swings reduced up to 10 ^{o}C and heating requirements reduced more than 17 % on a yearly base.

In another study, the possibility of increasing the energy performance of the thermal bricks by the application of PCMs was investigated by Principi and Fioretti [20]. In order to evaluate the effectiveness of the method, energy evaluation was conducted both theoretically and experimentally.

The application of PCM material has gained interest for energy conservation measures. However, the implementation of PCM material in LWB and heavyweight buildings (HWB) in hot regions of Iran has not been put into practice yet. Moreover, research studies based on the Typical Meteorological Year (TMY) weather data to estimate the yearly performance of the so-called buildings integrated with PCMs are very limited in the region and, actually, none to the best knowledge of the authors. For this purpose, this research is conducted and its major aim is to investigate the feasibility of PCM application in a high cooling load demanding region of Iran. This research was performed to evaluate the possible effects of PCMs in buildings' indoor air conditions and yearly required cooling load. The study was conducted in two different residential buildings such as one building with lightweight material and another building with heavyweight material. The considered building is located in southeast of the country as a representative of high cooling load demanding regions (Note that south and southeast regions of the country are considered as a high cooling load demanding region).

2. RESEARCH METHODOLOGY

Possible effects of PCM in two different buildings in terms of materials as the LWB and HWB were investigated in this research. To this end, the existing situation of the spaces in terms of indoor air conditions and required cooling load was evaluated first. Then, the PCM material as a thermal layer was added to the external walls of the buildings to determine the best performance of the new design. Different types of PCMs from the organic and inorganic categories were examined to recommend the best configuration for the buildings. EnergyPlus software was employed to investigate the performance in an hour-by-hour base. By the application of the EnergyPlus software the effects of the PCM layer on the indoor air conditions and cooling load of the spaces were determined and compared.

3. EnergyPlus SOFTWARE OVERVIEW

Literature review indicates that several systems and building energy simulation software's packages have been developed to be used by the engineers [21]; however, there are few building energy simulation software's packages, which are able to simulate the PCM material incorporated buildings [22]. EnergyPlus software [23] and TRNSYS [24] are extensively employed for the PCM modeling in buildings. However, because of the distinguished capabilities of EnergyPlus software (building energy simulation software), it was used in this study. EnergyPlus software as a simulation environment is capable of modeling thermal systems and designing and simulating buildings equipped with alternative energy systems.

In order to simulate the systems' performance for a yearly operation, the TMY weather data is required. The weather data files could be obtained by the EnergyPlus software weather database [25]. The simulation results could be determined hour-by-hour and, therefore, could be considered a reliable estimation of the energy unit's performance for a yearly operation.

4. DYNAMIC SIMULATION FOR A YEAR-ROUND OPERATION: THE EXISTING BUILDING AND THE BUILDING INCORPORATED WITH THE PCM LAYER

In this section, the simulation process and simulation results of the considered LWB and HWB are described. The simulation process is explained in subsection 4.2, and simulation results will be presented in section 5.

4.1. Climate Conditions

Chabahar is located on the Makran Coast of the Sistan and Baluchistan province, Iran. Chabahar has a hot climate with relatively high relative humidity (RH). The region is considered as a high cooling load demanding region. Fig. 1 illustrates the mean monthly ambient air temperature and RH values of the region.

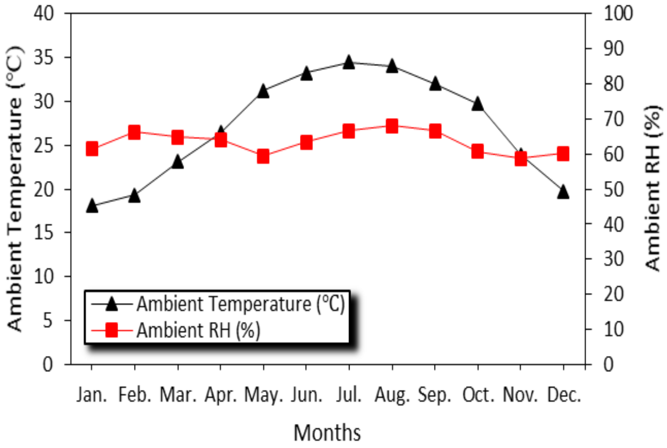


Figure 1. Monthly mean ambient air temperature and RH of the region.

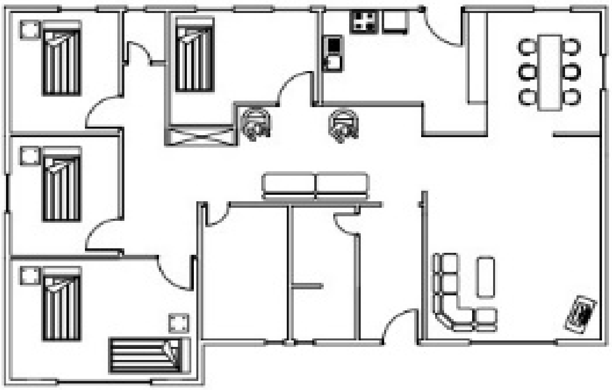
4.2. Buildings Simulation

Heat transfer phenomenon in the buildings is a complex issue. Indoor and outdoor conditions have a significant effect on the indoor thermal comfort and the energy performance of the buildings, especially when the PCMs are incorporated into the building walls structure. Buildings performance simulation provides the possibility of evaluating a wide range of situations to achieve improvements in the building energy performance and indoor thermal comfort.

4.3. Model Characteristics

As already mentioned, the considered buildings are located in southeast region of the country as a high cooling load demanding area. The LWB and HWB spaces are considered as a single thermal zone with 155 m^2 and 102 m^2 zone area, respectively. Figs. 2 and 3 show the overview and plan view of the LWB and HWB, respectively.

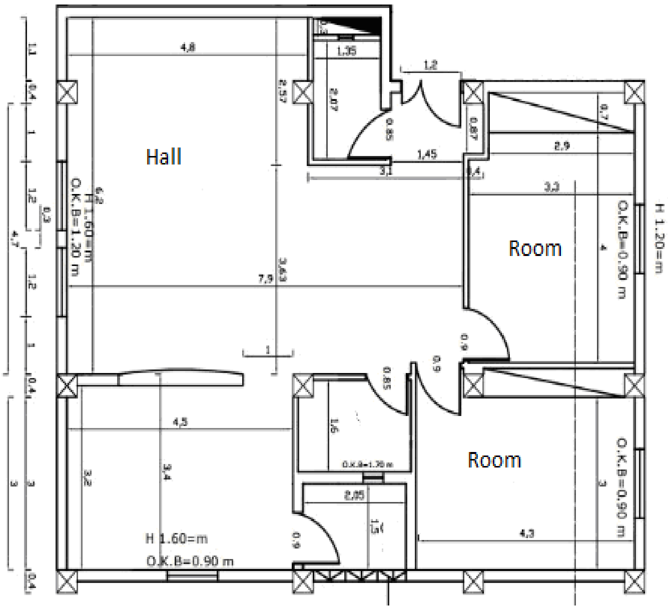
(a) Overview of the LWB



(b) Plan view of the LWB

Figure 2. (a) Overview of the LWB, (b) Plan view of the LWB.

(a) Overview of the HWB



(b) Plan view of the HWB

Figure 3. (a) Overview of the HWB, (b) Plan view of the HWB.

The architectural designs as well as the internal conditions were employed in the software to determine the thermal performance of the buildings. The external walls layout for the LWB and HWB cases are shown in Fig. 4 and 5, respectively. The construction specifications of the buildings are tabulated in Table 1.

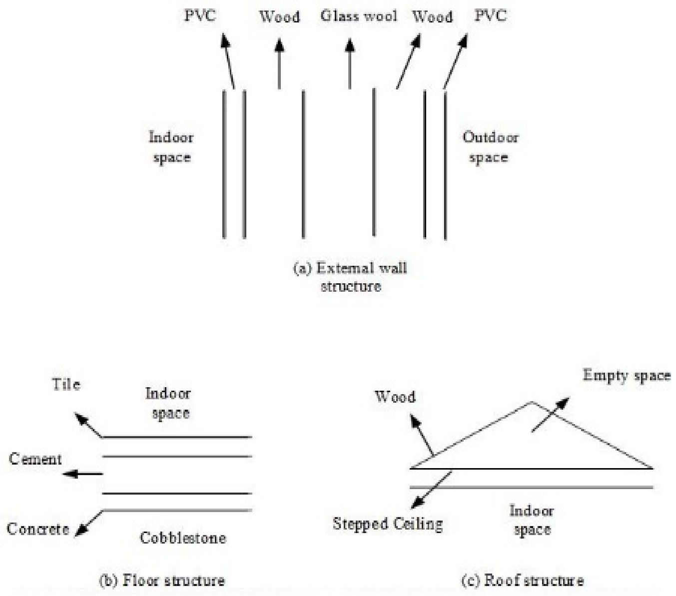


Figure 4. LWB external walls, floor, and roof structures layout: (a) External wall structure, (b) Floor structure, (c) Roof structure.

4.4. PCM Layer

TES system is considered as the one of the reliable and sustainable ways for energy storage in the buildings envelope. Energy saving in the buildings by the application of TES can be achieved in various methods.

Fig. 6 shows the storage materials classification including sensible, latent and chemical heat.

Thermal energy is normally stored in the buildings by the sensible heat of the construction materials. In addition, the storage capacity of the materials is related to the specific heat capacity and the mass of the construction materials applied in the building structure. For instance, LWB have low thermal energy storage capacity due to the envelop materials and integration of PCM could enhances the building storage capacity.

The working principle of the PCM is simple. PCM phase changes from solid to liquid with the rise of temperature and changes from liquid to solid as the temperature decreases. During this phase change process, PCM absorbs and desorbs heat. The phase change occurs at the phase change temperature without a significant rise in the temperature. The advantageous of latent heat storage such as PCM in comparison to the sensible heat storage materials is that a much larger volume of sensible heat storage material is needed to store the same amount of energy in comparison to latent heat storage.

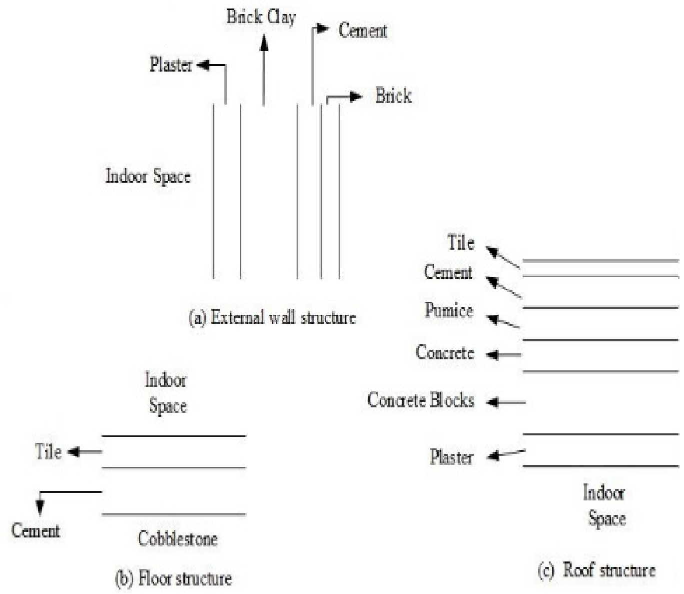


Figure 5. HWB external walls, floor, and roof structures layout: (a) External wall structure, (b) Floor structure, (c) Roof structure.

The PCM materials applied in buildings can be categorized into two main categories as the organic materials and inorganic materials. The organic PCM materials present a congruent phase change, they are not dangerous, and they have an acceptable nucleation rate. Organic materials are compatible with conventional materials of buildings construction. Availability in a large temperature range, ability to melt congruently, freeze without much super cooling, and self-nucleating properties are some of the organic PCM materials advantages. The inorganic PCMs are materials such as salt hydrates. High volumetric latent heat storage capacity, low cost and easy availability, high thermal conductivity, sharp phase change, and non-flammable are the advantages of inorganic PCM materials. In this study three types of organic PCM and three type of PCM from inorganic category were examined. The examined PCMs properties are tabulated in Table 2.

Table 1. Specifications of the buildings elements.

	$d(m)$	$\lambda(w/mk)$	$\rho(kg/m^3)$	$c(J/kgk)$
LWB case				
Eternal walls				
Wood	0.025	0.119	447.0	1630
Insulation	0.050	0.036	140.0	960.0
Wood	0.025	0.119	447.0	1360
PVC	0.050	0.190	1380	1005
Floor				
Tile	0.05	0.057	290	590
Cement	0.02	0.580	1900	1000
Roof				
Wood	0.025	0.119	447.0	1630
Air-Gap	0.400	-	-	-
HWB case				
Eternal walls				
Brick	0.01	0.890	1920	790

Cement	0.04	0.580	1900	1000
Brick-Clay	0.20	1.185	2240	790
Plaster	0.02	0.580	800	1090
Floor				
Tile	0.05	0.057	290	590
Cement	0.02	0.580	1900	1000
Roof				
Tile	0.05	0.057	290	590
Cement	0.02	0.580	1900	1000
Insulation	0.07	0.030	43.0	1210
Concrete	0.07	1.950	2240	900
Concrete Block	0.20	1.130	2210	920
Plaster	0.02	0.580	800	1090

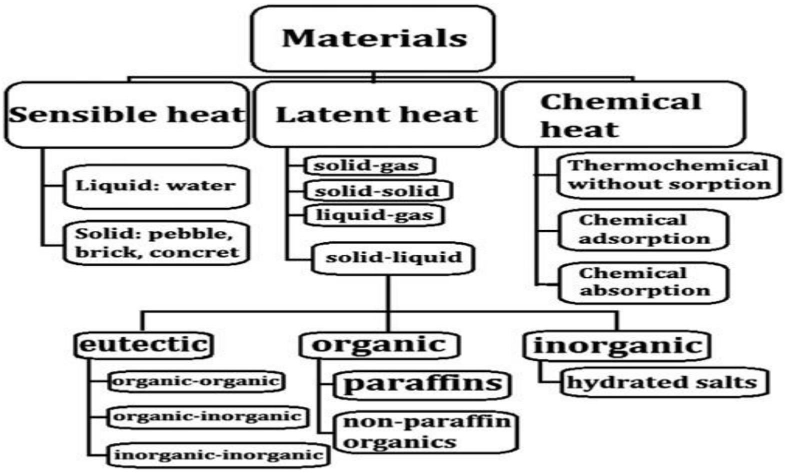


Figure 6. Classification of materials for TES [26].

Table 2. PCM material properties.

PCM	Type	Density (kg/m^3)	Melting point (^{o}C)	Specific heat (J/kg.K)	Heat of fusion (kJ/kg)
n-octadecane (N.OCT)	Organic	778	25.38	2169	243.5
n-eicosane (N.EIC)	Organic	790	35.00	2040	241.0
Paraffin Wax P116 (PWP116)	Organic	802	37.00	1900	225.0
Calcium chloride hex hydrate (CCH)	Inorganic	1556	30.00	1400	175.0
Salt Hydrate 47 (SH47)	Inorganic	Enthalpy-Temperature Chart			
Sodium Acetate Trihydrate (SAT)	Inorganic	Enthalpy-Temperature Chart			

Traditionally, PCM layers were used to stabilize interior building temperature; therefore, PCM layer was recommended to be in the interior building surfaces walls [27]. Therefore, in the first phase of the study, the PCM layers was planned to be added to the interior buildings surface.

5. SIMULATION RESULTS AND DISCUSSION

5.1. Existing space (Existing buildings) simulation results

The simulation results for the indoor air conditions and cooling load of the buildings were conducted hour-by-hour and mean monthly values were presented. Figs. 7 and 8 illustrate the hourly temperature and RH variation of the LWB and HWB, respectively. The indoor air temperate and RH for typical July, as the representative of the months of the year was presented. (Note: the simulations results were shown for July as the hottest month of the year). As illustrated in Figs. 7 and 8 for the LWB case, the indoor air temperature fluctuates between 34.4 ^{o}C and 41.2 ^{o}C with a mean value of 38 ^{o}C for the typical July. In addition, RH values vary from 34.1 % to 70.6 % with a mean value of 54.2 %.

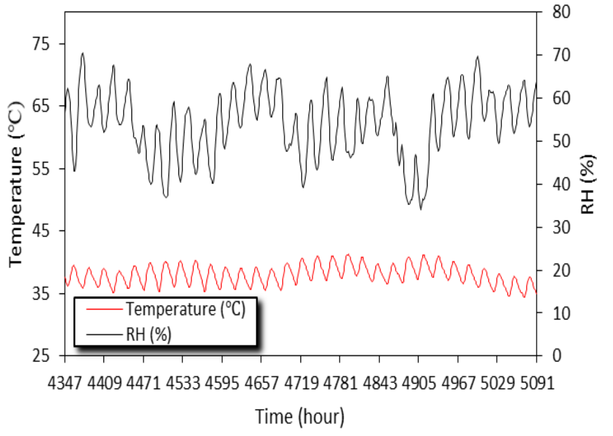


Figure 7. Hourly simulation responses of the existing space (LWB) for typical July.

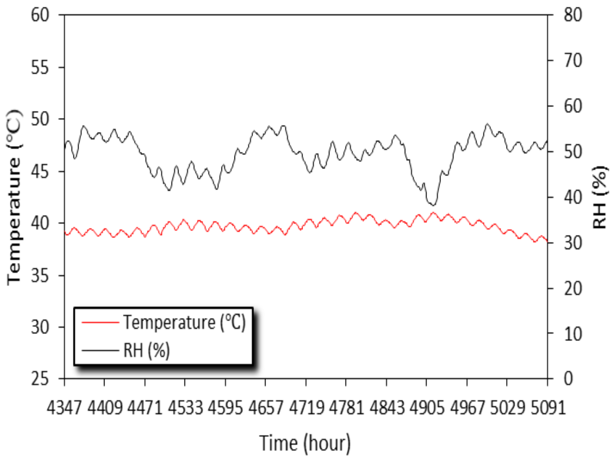


Figure 8. Hourly simulation responses of the existing space (HWB) for typical July.

For the HWB, the study shows the variation of indoor air temperature form 38.2 °C to 41 °C with a mean value of 39.7 °C. Moreover, for the RH value, the RH varies from 38.2 % to 56.3 % with a mean value of 49.6 % for the hottest month of the year. The complete simulation results were tabulated in Table 3 for the convenience.

To estimate the actual effect of the added PCM layer in the buildings, the yearly required cooling load of the buildings were also evaluated. Figs. 9 and 10 indicate the hour-by-hour required cooling load by the LWB and HWB, respectively for typical July as the representative of the moths of the year. The study shows that the total amount of 53.58 GJ cooling load was required by LWB and the total cooling load of 54.48 GJ was needed by HWB to establish the comfort thermal. The monthly required cooling load by the buildings was tabulated in Table 4.

Table 3. Mean indoor air temperature and RH- existing space (space without the PCM layer).

Month	LWB		HWB	
	I.T. (°C)	I.RH (%)	I.T. (°C)	I.RH (%)
Apr.	30.09	50.95	32.95	42.53
May.	34.62	51.14	36.42	45.82
Jun.	36.86	50.19	38.89	44.80
Jul.	37.76	55.35	39.70	49.57
Aug.	36.77	58.82	38.71	52.77
Sep.	35.23	56.52	37.92	48.25
Oct.	31.61	56.17	36.11	48.46
Nov.	25.22	54.38	30.56	39.53

By the comparison of the mean monthly indoor air temperature by the recommended indoor air conditions by the standards [28], the cooling load was not required for the whole months of the year. Therefore, the months, which the cooling load is required, were considered for the further simulations. According to the Table 3, these months are: April, May, June, July, August, September, October, and November. Therefore, application of PCM material for cooling load reduction purposes was examined for the mentioned months.

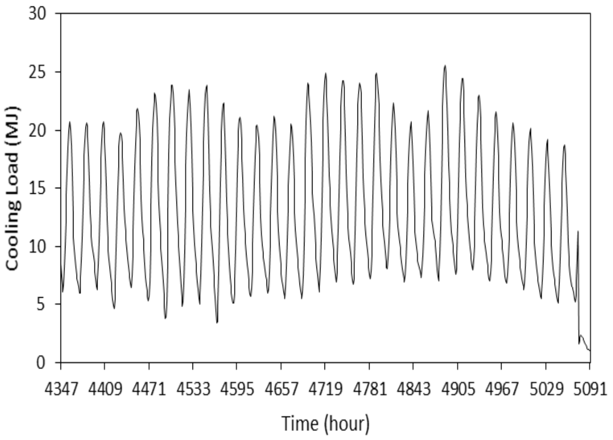


Figure 9. Hourly simulated required cooling load of the existing space (LWB) for typical July.

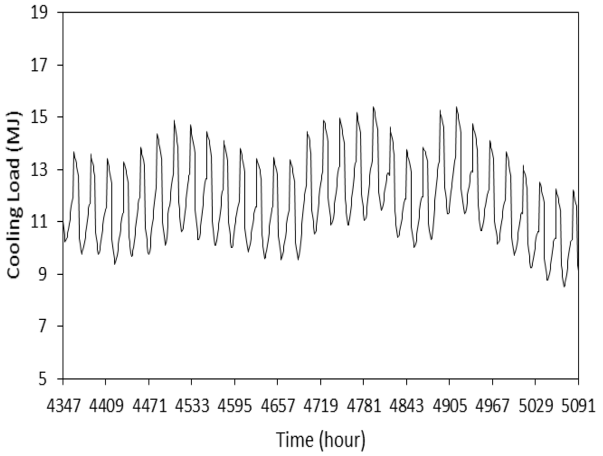


Figure 10. Hourly simulated required cooling load of the existing space (HWB) for typical July.

Table 4. Monthly required cooling load- existing space (space without the PCM layer).

Month	LWB [GJ]	HWB [GJ]
Apr.	3.840	5.060
May.	8.000	7.210
Jun.	8.860	8.070
Jul.	9.840	8.760
Aug.	9.070	8.170
Sep.	7.640	7.520
Oct.	4.980	6.430
Nov.	1.350	3.260
Total	53.58	54.48

In order to validate the existing spaces simulation values, the indoor air temperature and RH were measured. For this purpose, the anemometer was placed one meter above the floor, as this is the approximate distance for the space occupants recommended by the ASHRAE standards [29].

The fieldwork measurements and simulation results were tabulated in Table 5. As indicated in Table 5, the agreement between the fieldwork measurements and the simulated values is acceptable.

Table 5. Spot measured air conditions and simulated results for the buildings.

	Indoor air DBT (^{o}C)	**Indoor air RH (%)**
	LWB	
Field measurement results	49.9	26.8
Simulation results	46.19	25.00
Deviation (%)	6.81	5.54
	HWB	
Field measurement results	47.9	26.3
Simulation results	45.4	24.99
Deviation (%)	5.21	4.98

5.2. Simulation results for the buildings incorporated with a PCM layer

As already discussed above, the buildings with the added PCM layer were simulated for the eight months of the year, whose temperatures are not within the human thermal comfort range. Figs. 11-14 illustrate the hour-by-hour simulation results for the established indoor air temperature and RH for typical July for the LWB and HWB, respectively. In Figs. 11-14, buildings with the added N.EIC and PWP116 were shown, as the representative of the PCMs examined. However, the mean monthly values for all the examined PCMs were tabulated in Tables 6 and 7 for the convenience.

As shown in the Figs. 13 and 14 the indoor air temperatures have been significantly improved. For instance for typical July, for the LWB case, the indoor air temperature has been improved from 38 ^{o}C to 33.2 ^{o}C. In addition, the study showed that by the application of PCM layer in the HWB case, the indoor air reduced from 39.7 ^{o}C to 38.6 ^{o}C, see Figs. 13 and 14.

For instance, based on the simulation results for the LWB case, the mean indoor temperatures of 26 ^{o}C, 31.5 ^{o}C, 36.7 ^{o}C, 37.7 ^{o}C, 36.8 ^{o}C, 35.2 ^{o}C, 31.8 ^{o}C and 27.4 ^{o}C for Apr., May, Jun., Jul., Aug., Sep., Oct., and Nov. respectively could be achieved by the added N.EIC layer. In addition, the simulation results for the HWB case proved that the indoor air temperature would be 33.2 b ^{o}C 36.7 ^{o}C, 38.3 ^{o}C, 38.6 ^{o}C, 38.3 ^{o}C, 37.9 ^{o}C, 36.9 ^{o}C and 32.7 ^{o}C for Apr., May, Jun., Jul., Aug., Sep., Oct., and Nov., respectively with the help of PWP116 PCM layer (see Table 6 and 7).

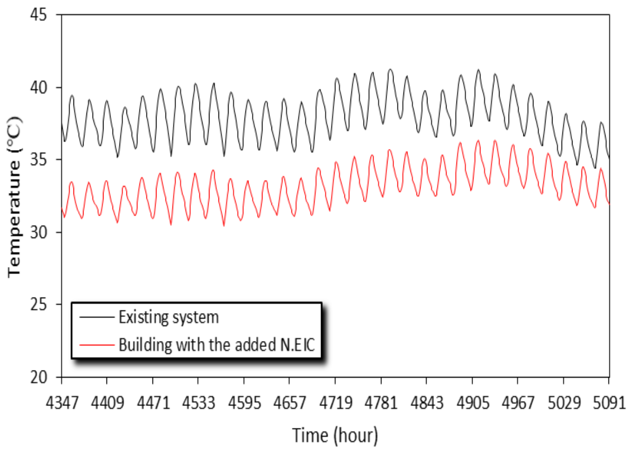


Figure 11. Hourly simulation responses for the LWB (with and without PCM layer) for typical July.

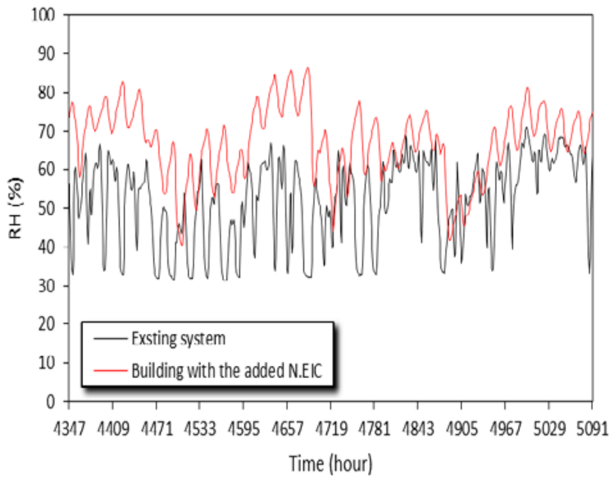


Figure 12. Hourly simulation responses for the LWB (with and without PCM layer) for typical July.

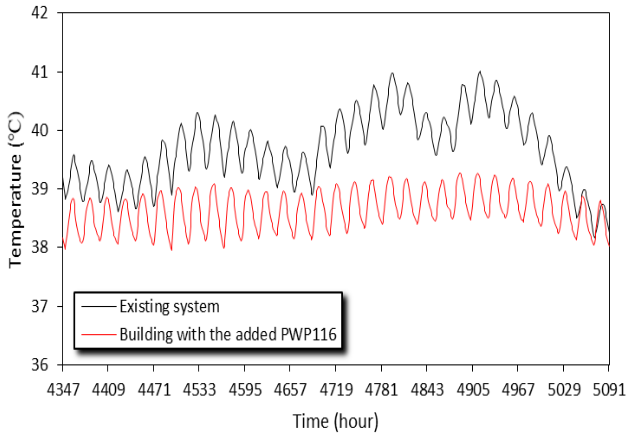


Figure 13. Hourly simulation responses for the HWB (with and without PCM layer) for typical July.

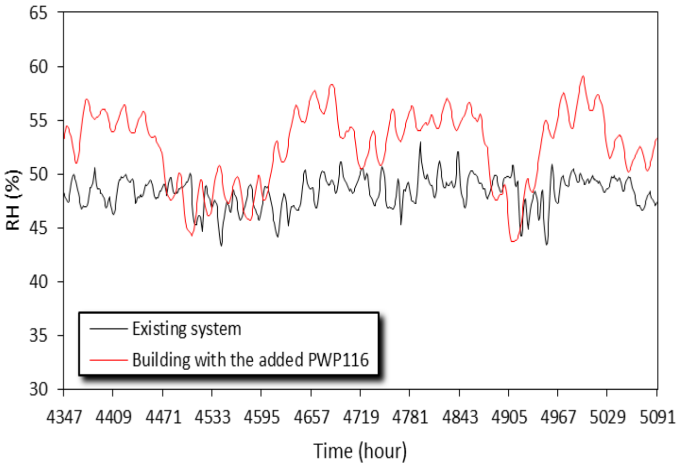


Figure 14. Hourly simulation responses for the HWB (with and without PCM layer) for typical July.

The cooling load of the buildings was also estimated for the buildings with the added PCM layer. Figs.15 and 16 show the hourly required cooling load by the buildings with the added PCM layer for the LWB and HWB, respectively. Fig. 15 illustrates the hour-by-hour required cooling load for the existing system (building without the PCM layer) and the building with the added N.EIC, as the representative of the

PCMs examined. Fig. 15 shows the effect of the added N.EIC as the PCM layer in typical July for the LWB case. As shown in Fig. 15, by adding the N.EIC layer to the LWB, the cooling load reduces from 9.65 GJ to 8.69 GJ.

The monthly required cooling load by the buildings with the added PCMs layer was tabulated for the LWB and HWB in Tables 8 and 9. The study revealed that by the application of the CCH layer in the LWB case the yearly cooling load of the LWB reduces from 53.58 GJ to 39.8 GJ, which is about 25.7 %. In addition, as tabulated in Table 9, the yearly reduction of 47.1 % could be achieved by the application of N.EIC layer for the HWB case.

Table 6. Box-Behnken design arrangement and response for PKBL synthesis.

Months	**Organic**						**Inorganic**					
	N.OCT		N.EIC		PWP116		CCH		SH47		SAT	
	I.T. (°C)	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**
Apr.	26.0	60.0	28.4	55.7	29.9	51.2	24.7	66.1	29.9	51.2	29.7	51.5
May.	31.5	58.0	30.8	58.3	34.3	52.0	26.8	75.3	34.4	51.7	34.2	52.3
Jun.	36.7	50.4	31.9	58.9	36.4	51.4	34.4	57.6	36.8	50.2	36.8	50.2
Jul.	37.7	55.3	33.1	64.5	37.1	57.6	37.8	55.2	37.7	55.3	37.7	55.3
Aug.	36.8	58.8	33.2	69.7	36.4	60.1	36.8	58.6	36.8	58.7	36.9	58.4
Sep.	35.2	56.7	32.0	65.9	35.1	57.0	35.3	56.2	35.2	56.5	35.3	55.9
Oct.	31.8	55.8	29.8	59.9	31.7	56.0	31.6	55.5	31.7	55.9	32.0	54.8
Nov.	27.4	48.8	25.1	55.4	25.5	54.2	24.7	56.1	25.5	54.2	26.0	52.3

Table 7. Mean indoor air temperature and RH- HWB Buildings with the PCM layer.

Months	N.OCT		N.EIC		PWP116		CCH		SH47		SAT	
	I.T. (°C)	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**	**I.T. (°C)**	**I.RH (%)**
Apr.	26.6	61.6	29.5	50.8	33.2	41.5	24.0	68.6	33.2	41.5	32.3	43.8
May.	32.3	54.8	30.3	60.8	36.7	45.0	30.6	59.7	36.9	44.5	35.9	46.9
Jun.	39.5	43.0	31.7	60.9	38.3	46.1	38.7	45.1	39.7	42.6	38.8	44.7
Jul.	41.1	45.5	38.9	54.1	38.6	52.5	39.9	48.6	40.7	46.6	39.9	48.7
Aug.	40.5	47.7	41.8	44.6	38.3	53.7	39.1	51.3	40.0	49.0	39.4	50.8
Sep.	39.7	43.5	41.6	39.3	37.9	48.0	38.3	47	39.2	44.8	38.5	46.5
Oct.	38.3	38.4	41.0	33.2	36.9	41.4	36.8	41.7	37.7	39.6	37.1	40.9
Nov.	33.6	33.9	39.4	24.4	32.7	34.9	31.7	37.1	32.8	34.7	32.4	35.5

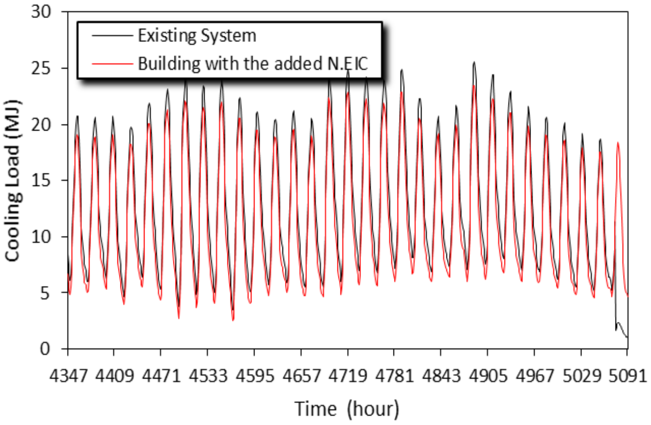


Figure 15. Hourly simulated required cooling load for LWB (with and without PCM layer) for typical July.

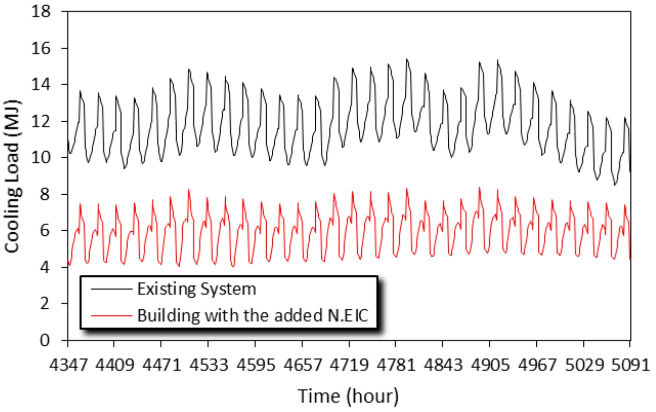


Figure 16. Hourly simulated required cooling load for HWB (with and without PCM layer) for typical July.

Yearly cooling load is a deciding parameter in the application of PCMs in buildings. Therefore, the PCM, which is able to reduce the maximum amount of yearly cooling load, is superior for the building. As tabulated in the Table 8, for the case of LWB, the yearly cooling load by the added PCM layers are 48.7 GJ, 47.5 GJ, 51.1 GJ, 39.8 GJ, 51.1 GJ, and 52.5 GJ with the added layers of N.OCT, N.EIC, PWP116, CCH, SH47, and SAT, respectively. It was also found that the yearly cooling load by the added PCM layer for the HWB case are 33.4 GJ, 28.8 GJ, 35.7 GJ, 41.4 GJ, 35.7 GJ , and 44.2 GJ for N.OCT, N.EIC, PWP116, CCH, SH47, and SAT, respectively.

Table 8. Monthly required cooling load-LWB with the PCM layer (GJ).

Months	**N.OCT**	**N.EIC**	**PWP116**	**CCH**	**SH47**	**SAT**
Apr.	1.95	3.44	3.59	1.07	3.59	3.61
May.	4.62	7.03	7.56	3.08	7.56	7.72
Jun.	6.60	7.81	8.49	5.22	8.49	8.71
Jul.	9.26	8.69	9.44	9.45	9.44	9.68
Aug.	9.34	8.04	8.69	8.92	8.69	8.92
Sep.	8.17	6.75	7.31	7.50	7.31	7.52
Oct.	6.15	4.41	4.75	4.20	4.75	4.94
Nov.	2.60	1.27	1.31	0.33	1.31	1.39
Total	48.7	47.5	51.1	39.8	51.1	52.5

Table 9. Monthly required cooling load-HWB with the PCM layer (GJ).

Months	N.OCT	N.EIC	PWP116	CCH	SH47	SAT
Apr.	1.51	2.87	3.51	0.80	3.51	4.13
May.	3.85	3.55	4.65	5.23	4.65	5.69
Jun.	4.74	3.91	5.10	6.69	5.10	6.42
Jul.	5.21	4.43	5.47	7.23	5.47	6.94
Aug.	5.03	4.27	5.16	6.77	5.16	6.51
Sep.	4.82	3.94	4.81	6.25	4.81	6.00
Oct.	4.61	3.53	4.34	5.49	4.34	5.37
Nov.	3.62	2.33	2.68	2.91	2.68	3.11
Total	33.4	28.8	35.7	41.4	35.7	44.2

As discussed above, the best performance in terms of yearly cooling load for the buildings with the added PCM was determined. The findings revealed that the CCH and N.EIC could provide the minimum required cooling load for the LWB and HWB, respectively.

6. PCM LAYER POSITOIN IN THE EXTERNAL WALL

As already mentioned, PCMs are normally used to stabilize interior building temperature; therefore, the PCMs were recommended to be added into the interior building walls structure. However, in this research the PCM layer position in the wall structure was also investigated to determine the optimum position in the wall structure layer. To this end, the recommended PCMs above were planned to be added to the external walls in three positions, namely interior layer, mid-layer, and external layer to investigate the effect of the position on the yearly required cooling load by the buildings.

CCH and N.EIC which already recommended for the LWB and HWB, respectively were considered for this phase of the research. As tabulated in Table 10, the added CCH layer to the LWB case has the optimum performance in terms of the yearly cooling load by incorporating the CCH into the internal layer of the external walls with about 39.77 GJ of yearly cooling load. However, the HWB has the best performance in terms of the yearly cooling load with the added N.EIC into the mid-layer of the external walls with about 27.9 GJ.

Table 10. Monthly required cooling load by the buildings, (GJ).

	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Total
	LWB (CCH)								
Internal layer	1.07	3.08	5.22	9.45	8.92	7.50	4.20	0.33	39.77
Mid-layer	2.80	6.12	7.98	9.74	8.97	7.56	4.95	1.30	49.42
External layer	2.81	6.40	8.77	9.73	8.95	7.55	4.90	1.08	50.19
	HWB (N.EIC)								
Internal layer	2.87	3.55	3.91	4.43	4.27	3.94	3.53	2.33	28.83
Mid-layer	2.70	3.30	3.50	3.96	4.35	4.05	3.75	2.29	27.9
Eternal layer	2.49	3.14	3.30	3.60	4.74	5.50	5.47	3.59	31.83

7. CONCLUSIONS

The possibility of improving the energy performance of the residential buildings by incorporating PCM in the external walls was investigated in the present research. The study was conducted in a high cooling load demanding region of Iran. Two types of buildings in terms of construction materials, namely LWB and HWB were considered. To this end, different PCMs from the organic and inorganic categories were examined to recommend the most desired PCM for the buildings in terms of yearly required cooling load. The buildings at the existing condition and the buildings with the added PCM layer were simulated using EnergyPlus to determine the buildings performance in terms of indoor air conditions and cooling load. The study revealed that the LWB has the optimum performance in terms of the cooling load by the adding the CCH layer to the building. It was found that by incorporating the CCH layer into the LWB envelop the yearly required cooling load of the LWB could be decreased about 25.7 %. In addition, it was shown that the yearly reduction of 47.1 % could be obtained by the application of N.EIC layer in the HWB case.

PCM layer position in the external walls was also explored. It was found that the added CCH layer to the LWB envelope has the optimum performance in terms of the yearly cooling load by incorporating the CCH .in the internal layer of the external walls. It was also proved that the HWB shows the best performance in terms of the yearly cooling load by adding the N.EIC layer into the mid-layer of the external walls.

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NOMENCLATURE

Abbreviations

ASHRAE	American society of heating, refrigerating and air conditioning engineers
CCH	Calcium chloride hex hydrate
EPW	EnergyPlus weather
HWB	Heavyweight building
I.RH	Indoor relative humidity
I.T	Indoor temperature
LWB	Lightweight building
N.OCT	n-octadecane
N.EIC	n-eicosone
PWP116	Paraffin wax P116
PCM	Phase change material
RH	Relative humidity
SH47	Salt hydrate 47
SAT	Sodium acetate trihydrate
TRNSYS	Transient system simulation software
TMY	Typical meteorological year
TES	Thermal energy storage

REFERENCES

1. International energy agency (IEA), World energy outlook, (2010).
2. Huang, Y., "Drivers of rising global energy demand: The importance of spatial lag and error dependence", ***Energy***, Vol. 76(C), (2014), 254-263. (https://doi.org/10.1016/j.energy. 2014.07.093).
3. U.S. energy information administration, https://www.eia.gov, (2009).
4. EU action against climate change: The european climate change programme, Luxembourg, (2006).
5. International atomic energy agency, https://www-pub.iaea.org, (2016).
6. Zarei, M. and Khademi Zare, H., "Energy consumption modeling in residential buildings", ***International Journal of Architecture and Urban Development***, Vol. 3, No. 1, (2013), 35-38.
7. Baetens, R., Jelle, B.P. and Gustavsen, A., "Phase change materials for building applications: A state-of-the-art review", ***Energy and Buildings***, Vol. 42, No. 9, (2010), 1361-1368. (https://doi.org/10.1016/j.enbuild.2010.03.026).
8. Sakulich, A.R. and Bentz, D.P., "Increasing the service life of bridge decks by incorporating phase change materials to reduce freeze-thaw cycles", ***Journal of Materials in Civil Engineering***, Vol. 24, No. 8, (2011), 1034-1042.
9. Raoux, S. and Wuttig, M., Phase change materials: Science and applications", Springer, (2009).
10. Zalba, B., Marín, J.M., Cabeza, L.F. and Mehling, H., "Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications", ***Applied Thermal Engineering***, Vol. 23, No. 3, (2003), 251-283. (https://doi.org/ 10.1016/S1359-4311(02)00192-8).
11. Alawadhi, E.M., "Thermal analysis of a building brick containing phase change material, energy and buildings, Vol. 40, (2008), 351-357. (https://doi.org/10.1016/j.enbuild.2007.03.001).
12. Tomas, V.T., Gaspar, U.L., Diego, A.V., Fabien, R. and Rodrigo, P., "Feasibility study of the application of a coling energy sorage system in a chiller plant of an office building located in Santiago, Chile". (https://doi.org/10.1016/j.ijrefrig.2019.01.028).
13. Ahmad, M., Bontemps, A., Salle´e, H. and Quenard, D., "Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material", ***Energy and Buildings***, Vol. 38, (2006) ,673-681. (https://doi.org/10.1016/j.enbuild.2005.11.002).
14. Gracia, A.D., Navarro, L., Castell, A., Ruiz-Pardob, L., lvarez, S. and Cabeza, L.F., "Thermal analysis of a ventilated facade with PCM for cooling applications", ***Energy and Buildings***, Vol. 65, (2013), 508-515. (https://doi.org/10.1016/j.enbuild.2013.06.032).
15. Nelson, S., Christoph, F.R. and Ali, H., "Simulation-based analysis of the use of PCM-wallboards to reduce cooling energy demand and peak-loads in low-rise residential heavyweight buildings in Kuwait", ***Building Simulation***, Vol. 10, No. 4, (2017), 481-495. (https://doi.org/10.1007/s12273-017-0347-2).
16. Solgi, E., Fayaz, R., MohammadKari, B., "Cooling load reduction in office buildings of hot-arid climate, combining phase change materials and night purge ventilation", ***Renewable Energy***, Vol. 85, (2016), 725-731. (https://doi.org/10.1016/ j.renene.2015.07.028).
17. Marina, P., Saffari, M., Gracia, A.D., Zhud, X., Farid, M.M., Cabeza, L.F. and Ushaka, S., "Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions", ***Energy and Buildings***, Vol. 129, (2016), 274-283. (https://doi.org/10.1016/j.enbuild. 2016.08.007).
18. Castell, A. Martorell, I., Medrano, M., Perez, G. and Cabeza, L.F., "Experimental study of using PCM in brick constructive solutions for passive cooling", ***Energy and Buildings***, Vol. 42, (2010), 534-540. (https://doi.org/10.1016/j.enbuild.2009.10.022).
19. Guarino, F., Athienitis, A., Cellura, M. and Bastien, D., "PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates", ***Applied Energy***, Vol. 185, (2017), 95-106. (https://doi.org/10.1016/j.apenergy. 2016.10.046).
20. Principi, P. and Fioretti, R., "Thermal analysis of the application of PCM and low emissivity coating in hollow bricks", ***Energy and Buildings***, Vol. 51, (2012), 131-142. (https://doi.org/ 10.1016/j.enbuild.2012.04.022).
21. Crawley, D.B., Hand, J.W., Kummert, M. and Griffith, B.T., "Contrasting the capabilities of building energy performance simulation programs", ***Building and Environment***, Vol. 43, (2008), 661-673. (https://doi.org/10.1016/j.buildenv.2006.10. 027).
22. AL-Saadi, S.N. and Zhai, Z.J., "Modeling phase change materials embedded in building enclosure: A review", ***Renewable and Sustainable Energy Reviews***, Vol. 21, (2013), 659-673. (https://doi.org/10.1016/j.rser.2013.01.024).
23. EnergyPlus, https://energyplus.net.
24. Transient system simulation tool (TRNSYS), http://www.trnsys.com.
25. EnergyPlus weather (EPW) data sources, https://energyplus.net/weather/sources.
26. Li, C. and Wangn, R.Z., "Building integrated energy storage opportunities in China", ***Renewable and Sustainable Energy Reviews***, Vol. 16, (2012), 6191-6211. (https://doi.org/10.1016/ j.rser.2012.06.034).
27. Kosny, J., Yarbrough, D.W., Miller, W., Petrie, T., Childs, P., Syed, A.M. and Leuthold, D., "Thermal performance of PCM-enhanced building envelope systems", ASHRAE, (2007).
28. ASHRAE, ASHRAE fundamentals, Atlanta, USA, ASHRAE, (2013).
29. ASHRAE. ASHRAE standard 55-2004, Atlanta, USA, ASHRAE, (2004).