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Optimal Design Method for Lightweight Buildings to minimize the Cooling Load with Phase Change Materials using Orthogonal Experimental Design

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Abstract. This study presents an investigation of the annual cooling load in buildings by analyzing the influence of parameters of phase change materials (PCMs) integrated into the envelopes of the buildings. For the use cases, well-known Cases 600 and 650 of ASHRAE Standard 140 were considered. We modified vertical walls of the use cases incorporating various PCM layers. The impact of various factors of PCM layers in four climates was assessed. These factors were the thickness, melting temperature, latent heat of fusion, density, specific heat capacity, and thermal conductivity. The results showed that the variation of the density, latent heat of fusion, and the thickness of PCMs had a high impact on the reduction of the annual cooling energy. However, the level of thickness, latent heat of fusion, and density stuck in the maximum value, whereas the level of thermal conductivity and specific heat capacity stuck in the minimum value. Generally, during the global and multi-objective optimization problems, these parameters may be excluded from the variable settings except for thickness whereby the penalty function can be set. The general thermodynamic pattern of the results concludes that buildings with lightweight envelopes require as much heat storage as possible preventing it from the flow of heat to the surrounding.

Keywords

Phase change materials; cooling load; orthogonal experimental design; ASHRAE Standard 140; lightweight buildings.

1. Introduction

Currently, the building sector consumes between 20% and 40% of the overall energy consumption in developed countries and emerging economies [1]. For example, in Germany, the energy consumed by the building sector was 28% of the end energy demand in 2016 [2], whereas the value for Uzbekistan was more than 50% [3]. Therefore, the most critical challenges are considered to reduce energy consumption and increase building energy efficiency in the world. Moreover, if the current building energy consumption were reduced by 20%, it would imply a decrease in CO_2 production of up to 50% compared to the current condition [4].

Although, the modern architectural design tends toward the highly glazed surfaces and lightweight materials in new buildings [5]. Typically, the required thermal resistance of the buildings is achieved using sufficient insulation materials. However, the desired reduction of energy consumption cannot be achieved due to the limit of wall thickness and low heat capacity of insulation materials [6,7]. Nevertheless, this reduction can also be significantly assisted by embedding PCMs into building's envelopes [8-10]. In this regard, the mathematical modeling of PCMs and whole systems is essential for optimal design and material selection [9,10].

Building design methods to minimize operational energy use have also been considered more and more critical recently [11]. For example, Bambrook et al. [12] developed a simple model for a detached house in Sydney and optimized the annual heating and cooling requirements with building performance simulation (BPS) tools. Crawford et al. [13] proposed a comprehensive model for streamlining low-energy building design. Magraner et al. [14] carried out a comparison between the design and actual energy performance of an HVAC-ground coupled heat pump system in cooling and heating operation. Genetic algorithms were used to find an optimal design method for building energy systems in [15].

Nowadays, few studies have explored the application of orthogonal experimental design (OED) to optimize building design for the lowest energy consumption [11]. Practical work usually requires multi-factor analysis and multi-factor experiments, including a full factorial experimental design (FED) and fractional FED [16]. Full FED tests all possible combinations of factors, and the number of trials gets extremely large. The OED is a multi-factor experiment design method based on the orthogonal array. It selects representative points from the full FED in a way that the points are distributed uniformly within the test range and thus can represent the overall situation. It is highly efficient for the arrangement of multi-factor experiments with optimal combination levels.

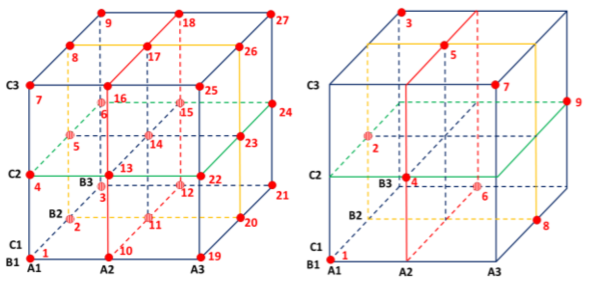
This work investigates the annual cooling energy in buildings analyzing six influential factors of PCMs integrated into external walls of buildings. The factors were thickness, melting temperature, latent heat of fusion, density, specific heat capacity, and thermal conductivity and with five values (levels). The study aims to find the most influential parameters of PCMs integrated into building envelopes, the variations of which significantly reduce the annual cooling energy. The results show that the variation of the density, latent heat of fusion, and the thickness of PCMs had a high impact on the reduction of the annual cooling energy. The general thermodynamic pattern of the results concludes that lightweight buildings require as much heat storage as possible while preventing it from the heat flow to the environment.

2. Methodology

A. Full factorial and orthogonal experimental designs

Many experiments involve the study of the effects of two or more factors. By the full FED, in each complete trial of the experiment, all possible combinations of levels of factors are investigated [16]. Fig. 1a shows a graphical representation of a 3^3 full FED for three (A, B, and C) independent variables at three levels of each. The full FED provides 27 of combinations requiring 27 of runs. Each number at the nodes of the cube (Fig. 1a) is the order of trials with a respective combination of factors at their different levels. For example, in experiments with the order of 1, 14, and 27, combinations of $A_1B_1C_1$, $A_2B_2C_2$, and $A_3B_3C_3$ are tested, respectively.

As an alternative to the full FED, the orthogonal experimental design (OED) method was proposed by Zhu et al. [11]. The OED method selects representative points from the full FED in a way that the points are distributed uniformly within the test range and thus can represent the overall situation. This method is highly efficient for the arrangement of multi-factor experiments with optimal combination levels. Fig. 2b shows that the number of experiments in the OED is reduced from 27 to 9 compared to the full FED, whereas the maximum uniformity of distribution of combination is achieved. In trials of 1, 6, and 9, combinations of $A_1B_1C_1$, $A_2B_3C_1$, and $A_3B_3C_2$ are tested. Fig. 2a shows that there is no combination of factors with the same indexes.



a) b)

Fig. 1. Examples of 3^3 full FED and OED for three (A, B and C) independent variables with three levels of each.

The OED has several advantages: the data points are distributed evenly; the number of trials needed to complete the experiment is relatively small; the test results can be analyzed through range analysis and variance analysis [11,16]. The OED has the following characteristics: use a fractional FED instead of the full FED, and understand the complete experiment through the study of the fractional experiment.

B. Orthogonal table

The number of levels in the OED should be equal to the number of levels in the orthogonal table. The number of factors (including interactions) should not exceed the number of the orthogonal table's columns. Six influence factors of the PCM layer were thickness, melting temperature, latent heat of fusion, density, specific heat capacity, and thermal conductivity. Each influence factor has five levels. Table 1 shows the six factors and five level values. No interactions between the factors were taken into account. Therefore, $L_{25}(5^6)$ was chosen from the orthogonal table to arrange the orthogonal design. It follows that we have to perform 25 tests instead of 5^6=15,625. Table 3 presents the orthogonal table for 25 tests conducted in the case of Climate I for the modified Case 600.

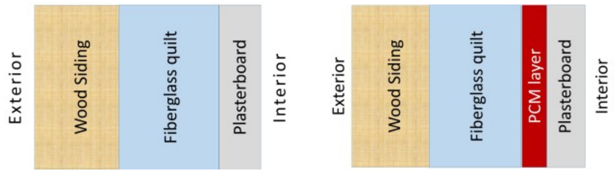
C. Use cases: basic Cases 600 and 650

In this study, modified Cases 600 and 650 of ASHRAE Standard 140 were tested and compared to the simulation data performed for their basic cases [17]. Case 600 was selected for its simplicity and because it is a well-referenced and understood test case that has been simulated by several BPS tools. The basic test case is a lightweight, rectangular, single-zone building, with dimensions of 8 m × 6 m × 2.7 m. The case has no interior partitions, total window area of 12 m^2 on the south wall, interior loads of 200 W (60 % radiative, 40 % convective) and a highly insulated slab to eliminate thermal ground coupling essentially. The in infiltration was set to 0.5 air changes per hour. The mechanical system of the building is an ideal system with 100% convective air system and an efficiency of 100% with no duct losses and no capacity limitation. The thermostat is set with a dead band, so heating takes place for temperatures below 20°C and cooling for temperatures above 27°C.

Case 650 has night ventilation. However, Case 650 is modeled the same as Case 600 except for the setting the thermostat and ventilation fan that has the following control strategies: from 18^{00} to 07^{00}, vent fan = ON; from 07^{00} to 18^{00}, vent fan = OFF; heating = always OFF; from 18^{00} to 07^{00}, cool = OFF; from 07^{00} to 18^{00} hours, cool = ON if the indoor temperature > 27°C; otherwise, cool = OFF. The ventilation operates with 1703.16 m^3/h of the volumetric flow rate. There is no waste of heat from the fan.

D. Modification of use cases 600 and 650

For the modification of Cases 600 and 650 by incorporating a PCM layer, only vertical walls were modified, as shown in Fig. 2b. All properties of basic materials of the wall were kept the same as for Case 600 of ASHRAE Standard 140 [17]. No additional changes were made. Properties of the PCM layer are selected from the orthogonal table (Table 3) using the combination of parameters given in Table 1.



a) Basic case (b) Modified case

Fig. 2. A schematic view of the external wall's layers in the basic and modified cases of ASHRAE Standard 140 [17].

E. Selection of PCMs and climates for case studies

We test PCMs with properties given in Table 1, supposing that at each trial, a corresponded PCM exists. Also, each parameter of PCMs varies independently. The main idea is to find the highest and lowest impact of factors individually. The factors A, B, C, D, E, and F correspond to thickness (mm), melting temperature (°C), latent heat of fusion (J/g), density (g/cm^3), specific heat capacity (J/g·K), and thermal conductivity (W/m·K), respectively.

Table 1: Influence factors and level values of PCM layers.

Level	Factors A	B	C	D	E	F
1	2	19	19.25	0.22	1.3	0.08
2	4	22	38.5	0.44	1.7	0.15
3	5	25	77	0.66	2.1	0.2
4	7	27	154	0.88	2.5	0.3
5	10	29	231	1.2	2.9	0.5

The annual cooling energy was assessed in the following climate conditions defined according to Köppen-Geiger classification [18]: Climate I – dry-cold semi-arid climate – BSk-Denver, Colorado, USA; Climate II – temperate oceanic climate – Cfb-Cologne, Germany; Climate III – Mediterranean-influenced hot-summer humid continental climate – Dsa- Tashkent, Uzbekistan; Climate IV – dry-hot desert climate BWh-Cairo, Egypt. All test cases were studied in one full-year weather data with an hourly time step.

F. AixLib – a Modelica-based library

AixLib is a Modelica model library with a focus on modeling the dynamic behavior of buildings. It includes HVAC equipment and distribution networks to enable integrated analyses of energy systems on the scales from a single building to city district [19]. Also, AixLib includes all validated basic test cases of ASHRAE Standard 140 [24]. For the facility of the comparative testing of modified test cases, we used basic test cases 600 and 650 from AixLib. All simulation of the unsteady heat transfer model in buildings were performed with models of *AixLib* in the environment Dymola.

G. Verification and validation

Verification and validation of the PCM model developed in Modelica were carried out using a similar approach interpreted in ASHRAE Standard 140 [17]. This approach consists of empirical validation, analytical verification, and comparative testing. For the thermal behavior of PCMs, three simple temperature-depend continuous functions were proposed and validated with experimental adiabatic scanning calorimetry data [20]. The heat transfer model for a single PCM-enhanced wall was verified analytically using the one-phase Stefan problem in page 40 of [23]. Also, the heat transfer model for a multi-component wall integrated with a PCM layer was comparatively tested [21]. The model was empirically validated on a whole-building level using measured data of a real-scale laboratory test room [22]. Lastly, the PCM model was comparatively tested on a whole-building level against simulation data performed for basic Cases 600, 600FF, and 650FF of ASHRAE Standard 140 [17].

H. Assumptions in this study

It assumes that PCMs with given properties at each trial exist. This supposing enables finding the best PCMs with quasi-ideal properties to minimize the annual cooling energy in different climates. The main goal of this assumption is to include as much input parameters as possible as variables while attempting to find the highest and lowest impacts of parameters at the same experiments. Moreover, this study deals only with local optimal problems while not dealing with global optimization problems. However, for further studies, global optimization problems can be considered.

3. Results and discussion

A. Annual cooling loads

Table 2 shows the annual cooling energy in basic (without PCM layer) and modified Cases 600 and 650. In the modified cases, the annual cooling energy is given for the best PCMs with quasi-ideal properties. For example, for the basic Case 600 in Climate I, the annual cooling energy in the basic case was 6.735 MWh, whereas the lowest annual cooling energy in the modified case during the performed tests was 4.376 MWh that can be seen in Table 3, where it comes from the test with the number of 17. Analogically, the rest lowest annual cooling energies come from the tests accordingly.

Table 2. Annual cooling energy in Cases 600 and 650.

Climates	Annual cooling energy in MWh Case 600 Basic	Case 600 Modified	Case 650 Basic	Case 650 Modified
I	6.735	4.376	5.234	2.125
II	2.924	1.886	2.254	1.018
III	7.926	6.544	6.113	3.860
IV	9.119	8.079	7.245	5.298

Table 3. Assessment of annual cooling energy using the orthogonal experimental design for Case 600 in Climate I.

Number of tests	Factors A	B	C	D	E	F	Cooling energy, *MWh*
1	1	1	1	1	1	1	6.525
2	1	2	2	2	2	2	6.391
3	1	3	3	3	3	3	6.071
4	1	4	4	4	4	4	5.480
5	1	5	5	5	5	5	5.194
6	2	1	2	3	4	5	6.018
7	2	2	3	4	5	1	5.355
8	2	3	4	5	1	2	4.596
9	2	4	5	1	2	3	5.804
10	2	5	1	2	3	4	6.319
11	3	1	3	5	2	4	5.229
12	3	2	4	1	3	5	5.929
13	3	3	5	2	4	1	4.959
14	3	4	1	3	5	2	5.911
15	3	5	2	4	1	3	5.869
16	4	1	4	2	5	3	5.270
17	4	2	5	3	1	4	4.376

18	4	3	1	4	2	5	5.675
19	4	4	2	5	3	1	5.042
20	4	5	3	1	4	2	6.101
21	5	1	5	4	3	2	4.565
22	5	2	1	5	4	3	4.816
23	5	3	2	1	5	4	5.981
24	5	4	3	2	1	5	5.281
25	5	5	4	3	2	1	5.171
K_1	29.66	27.61	29.25	30.34	26.65	27.05	
K_2	28.09	26.87	29.30	28.22	28.27	27.56	
K_3	27.90	27.28	28.04	27.55	27.93	27.83	
K_4	26.46	27.52	26.45	26.94	27.37	27.38	
K_5	25.81	28.66	24.90	25.75	27.71	28.10	
k_1	5.932	5.521	5.849	6.068	5.329	5.411	
k_2	5.619	5.373	5.860	5.644	5.654	5.513	
k_3	5.580	5.456	5.607	5.509	5.585	5.566	
k_4	5.293	5.503	5.289	5.389	5.475	5.477	
k_5	5.163	5.731	4.980	5.151	5.542	5.620	
Range R	*0.770*	*0.358*	*0.881*	*0.917*	*0.325*	*0.209*	
Relative domination	**22.3**	**10.3**	**25.5**	**26.5**	**9.4**	**6.0**	
Order	***D>C>A>B>E>F***						
Optimal Level	***A_5***	***B_2***	***C_5***	***D_5***	***E_1***	***F_1***	
Optimal Combination	***$A_5B_2C_5D_5E_1F_1$***						

B. *Determination of factor order*

The annual cooling energy in the *i*th level is summed and denoted by K_i, whereas k_i is the average value of K_i. For example, K_2 for the factor B is the summation of five annual cooling energies according to the factor B with the number of level of *2*, whereas k_2 is the average value of K_2 (Table 3). The order of factors is listed according to a size of ranges (R). The range R is the difference between maximum and minimum values among k_1 and k_5. The larger the range is, the more influence on the test results the level change of this factor has.

The factor that has the biggest range has the highest impact. The relative domination (%) is a relation of the range R of the corresponding factor to the sum of ranges of all factors. For example, the calculation performed for Climate I is presented in Table 3, the order of range is $R_D > R_C > R_A > R_B > R_E > R_F$. The order of factors influence level (OFIL) is D>C>A>B>E>F, which means that the OFIL of PCM layer follows as density > latent heat of fusion > thickness >melting temperature > specific heat capacity > thermal conductivity. Thus, in the given climate condition and values of parameters, the density of PCM layers has the highest impact on the annual cooling load, whereas thermal conductivity has the lowest effect.

C. *Determination of optimal case*

The ASHRAE Standard 140 provides the hourly and annual cooling/heating loads for one full year [17]. In this study, only the annual cooling energy is used, which is an integral of the hourly cooling load within one year. The optimal combination of factors and levels is based on the minimal annual cooling energy. The smaller k_i, the smaller the annual cooling load. For Case 600 in Climate I (Table 3), the orders of k_i for the factors of A, B, C, D, E, and F, $k_1>k_2>k_3>k_4>k_5$, $k_5>k_1>k_4>k_3>k_2$, $k_1>k_2>k_3>k_4>k_5$, $k_1>k_2>k_3>k_4>k_5$, $k_2>k_3>k_5>k_4>k_1$, and $k_5>k_3>k_2>k_4>k_1$, respectively. Thus, the lowest value of k_i is selected for the optimal combination, which is $A_5B_2C_5D_5E_1F_1$. In Climate I, thickness, melting temperature, latent heat of fusion, density, specific heat capacity, and thermal conductivity of the optimal PCM layer should be 10 mm, 22°C, 231 J/g, 1.2 g/cm^3, 1.3 J/(g·K), and 0.08 W/(m·K).

Due to the limitation of space, the complete results only for Climate I (Table 3) are provided. Table 4 presents the optimal combinations and optimal cooling load reductions for Cases 600 and 650 in different climates. For Case 600, the same domination of factors and the corresponding optimal combination in Climate II are obtained. The same optimal combination of parameters in Climate III is obtained, but with D>C>A>F>E>B, where the variation of melting temperature has the lowest impact within given values in the continental climate condition. In Climate IV, we obtained D>C>A>B>F>E, where the variation of the specific heat capacity has the lowest impact. The optimal combination of parameters for a PCM layer was $A_5B_4C_5D_5E_3F_1$. This combination indicates the necessity of higher melting temperature (27°C) that was expected in the dry-hot desert climate.

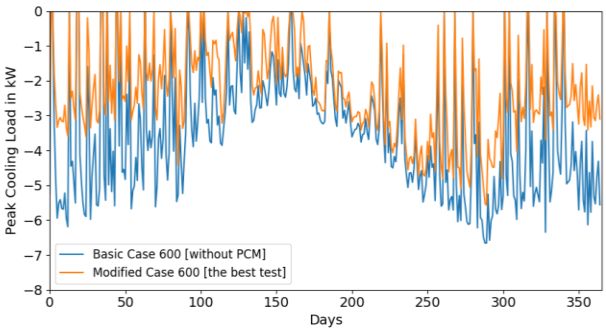
Table 4. Optimal combination (OC) and optimal annual cooling load reductions for Cases 600 and 650 in different climates.

Climates	*Reduction in the annual cooling energy, %*			
	OC	**Case 600**	**OC**	**Case 650**
I	$A_5B_2C_5D_5E_1F_1$	35.03	$A_5B_1C_5D_5E_1F_1$	59.39
II	$A_5B_2C_5D_5E_1F_1$	35.50	$A_5B_1C_5D_5E_1F_1$	54.85
III	$A_5B_2C_5D_5E_1F_1$	17.44	$A_5B_1C_5D_5E_1F_1$	36.85
IV	$A_5B_4C_5D_5E_3F_1$	11.40	$A_5B_4C_5D_5E_1F_1$	26.87

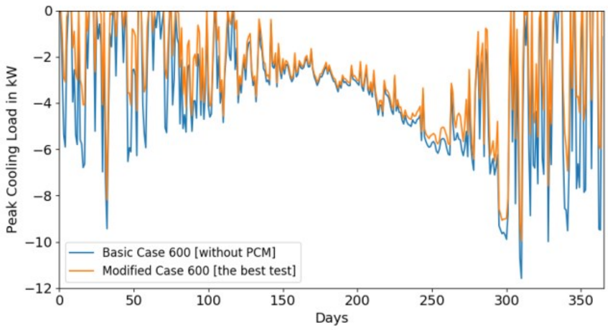
Following the same approach, D>A>C>B>F>E is obtained for Case 650 in Climate I. The optimal combination of parameters is $A_5B_1C_5D_5E_1F_1$. Only the level of the melting temperature has changed compared to Case 600. During the test of Case 650 in Climate II, the same OFIL of Climate I is obtained. However, the optimal combination is $A_5B_1C_5D_5E_1F_1$. In Climate III, the OFIL is D>A>C>F>E>B. The optimal combination is the same for Climate I. Within the test of Case 650 in Climate IV, the OFIL is D>A>C>E>F>B, where the optimal combination is $A_5B_4C_5D_5E_1F_1$.

D. *Analysis of daily peak cooling loads*

We presented daily peak cooling loads for basic and modified Cases 600 and 650 in Climates I and III due to the limitation of space. Fig. 3 shows daily peak cooling loads for both basic and modified Cases 600 in Climate I and III. As seen in Table 4 and Fig. 3a, the cooling load for Case 600 decreased significantly using the best PCM layer. Fig. 3a represents the daily peak cooling load corresponding to the test with the number of 17 in Table 3, which is the best test among observed tests.

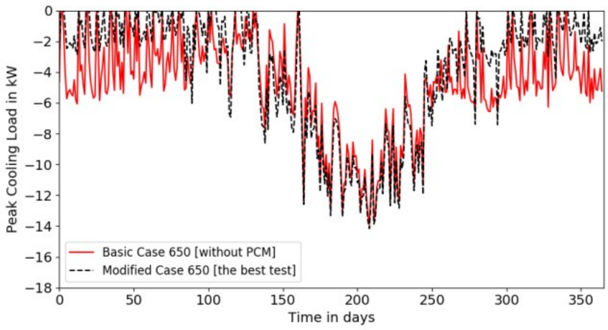


a) Climate I

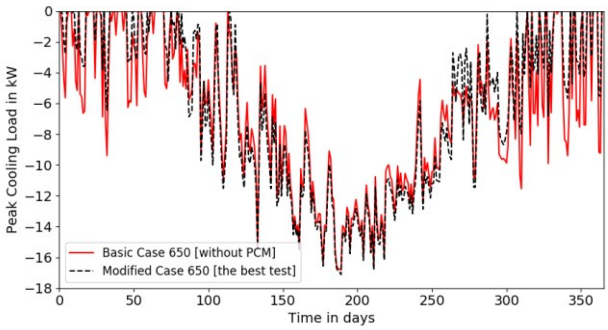


b) Climate III
Fig. 3: Daily peak cooling loads for basic and modified Cases 600 in Climate I and III.

Fig. 3b also represents the daily peak cooling load for basic and the modified Case 600 in Climate III, which is reduced insignificantly compared to Climate I. The insignificant reduction of the annual cooling energy can also be seen in Table 4. Both Fig. 3a,b indicate that even the best PCM does not reduce the peak cooling load significantly during hot summer days, because both Climate I and III represent dry-hot summer days.



a) Climate I



b) Climate III
Fig. 4: Daily peak cooling loads for basic and modified Cases 650 in Climate I and III.

Fig. 4a and b show daily peak cooling loads for both basic and modified Cases 650 in Climate I and III. Fig. 4a represents the daily peak cooling load corresponding to the best in Table 4. Case 650 has scheduled thermal control and night ventilation that contribute significantly to minimize the cooling load in buildings with PCMs.

E. Additional analysis: a heavyweight building

We additionally tested Case 600 in Climates I, and III with a different thermal mass of the external walls. In order to do so, an extra layer between the fiberglass and PCM layer (see Fig. 2b) is introduced. The thickness of the layer is 10 cm; other properties are the same as plasterboard's (Fig. 2b). The modified Case 600 is now a heavyweight building. We repeated the full test running 25 trials. The results for Climate I show that the order of factor influence levels (OFIL) is F>D>E>B>A>C for the specific annual cooling load. In the case of a heavyweight building, a variation of thermal conductivity has the highest impact on the annual cooling load, whereas a variation of latent heat of fusion has the lowest effect. The optimal test is $A_4B_3C_1D_4E_2F_5$, where the thermal conductivity (factor F) reaches the highest value and the latent heat of fusion reaches the lowest value (factor C). In order to reduce a cooling load in heavyweight buildings significantly, PCMs with high thermal conductivity should be incorporated.

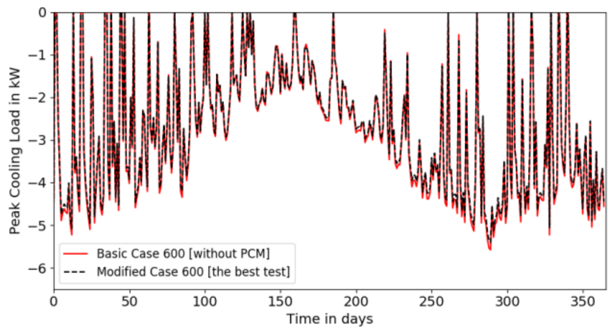


Fig. 5: Daily peak cooling loads for basic and modified Cases 600 in Climates I (a heavyweight building).

In Climate III, the OFIL is D>F>B>E>C>A which indicates that a variation of density has the highest effect on the specific annual cooling load, while a variation of thickness has the lowest effect. However, a variation of thermal conductivity has still higher effect than in the case of low thermal mass.

Thus, to reduce the cooling load in heavyweight buildings by the incorporation of a PCM layer, the thermal conductivity of PCM layers plays an important role. In cooling periods, the annual cooling load was significantly affected by a variation of thermal conductivity, while the variation of latent heat of fusion effects insignificantly. In the best test, the annual cooling energy decreases only by 1.46%. Fig. 5 proves this value by presenting the daily peak cooling load in basic and modified Case 600. Fig. 5 shows that the integration of a PCM layer into heavyweight buildings is inexpedient.

4. Conclusion

In this study, a design method is presented for the integration of optimal PCMs into building envelopes to minimize the annual cooling energy using the orthogonal experimental design method. Therefore, as the use cases, well-known models of buildings – Cases 600 and 650 of ASHRAE Standard 140 were considered. The external walls of the use cases were modified by incorporating various PCM layers. The impact of various factors of PCM layers in different climates was assessed. These factors were the thickness, melting temperature, latent heat of fusion, density, specific heat capacity, and thermal conductivity. The use cases were studied in four climates classified according to Köppen-Geiger classification: dry cold semi-arid climate; temperate oceanic climate; Mediterranean-influenced hot-summer humid continental climate; dry hot desert climate.

For lightweight buildings, the results showed that the density, latent heat of fusion, and the thickness of PCMs had a high impact on the reduction of the annual cooling energy not depending on the ventilation mode. However, the level of thickness, latent heat of fusion, and density stuck in the maximum value, whereas the level of thermal conductivity and specific heat capacity stuck in the minimum value. During the global and multi-objective optimization problems, the variation of the parameters may be eliminated from the variable settings except for thickness whereby the penalty function can be sets. The general thermodynamic pattern of the results concludes that lightweight buildings require as much heat storage as possible while preventing it from the heat flow to the environment.

An additional test of Case 600 in Climate I and III with the higher thermal mass of the external walls shows that in the case of a heavyweight building, the thermal conductivity has the highest impact on the cooling load, whereas the latent heat of fusion has the lowest effect. It follows that the thermal conductivity of PCMs should be enhanced when integrating PCM layers into heavyweight buildings. In conclusion, it should be noted that the method of OED has allowed mapping the pattern of the effect of parameters of PCM layers on the reduction of the cooling load while enabling to find their unimportant factors.

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