Evaluation of Building Envelope Performance Constructed with Phase-Change Materials in Terms of Heating and Cooling Energy Consumption

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It is a priority to take precautions in the building envelope design as the building envelope is the determinant of these energy consumptions. One of the new approaches used to control the heat transfer of the building envelope is phase-change materials. In this study, in a single-storey building, a 10 m / 10 m sized zone, in Diyarbakır (hot and dry climatic zone) and in Erzurum (cold climatic zone) was taken into consideration. Only the southern facade of the determined zone has a transparent component in order to reduce the heating loads, the phase-change material was applied in the building envelope of the studied zone. The thickness of the phase change material and the percentage of the transparent component on the applied surface were increased at every step, and alternatives of different building envelopes were created. For every different alternative, annual heating and cooling energy consumptions of the zone were calculated.

Today, majority of the energy consumed in the world is used in buildings. This rate is approximately 30% for buildings in Turkey [1]. Studies mostly focus on heating energy consumption when energy consumed in buildings is discussed and reduction on energy consumption is generally concentrated on heating energy. However, cooling demand in buildings is also increasing as the side effect of the climate change [2]. Therefore, reducing cooling energy consumption has also become a necessity.

When we look at cooling and heating energy consumptions and comfort requirements for different climate regions in residential buildings in Turkey, we see that the distribution of energy consumption and priorities (heating-cooling) vary depending on the climatic region. Reduction of cooling energy consumption is important in hot-dry climatic regions while reduction of heating energy consumption is important in cold climatic regions. Based on the above, it is possible to reduce energy consumptions by taking the right decisions about the variables which affect heating and cooling energy loads in buildings in different climatic regions [1,3].

A building envelope, a component which separates indoor from outdoor, is an important variable that plays a role in converting and transferring the effects of outdoor climate conditions to indoors and in creating indoor thermal comfort conditions depending on its thermo-physical properties [3]. Therefore, every decision regarding a building envelope can have a direct effect on the energy consumption of the zone enclosed by the envelope and vary depending on the climatic conditions [4].

Phase Change Material (PCM) applications on building envelopes use the materials' thermal energy storage properties to reduce heating, cooling and total energy consumption. PCMs can be defined as innovative materials alternative to conventional thermal mass, which absorb heat and stores in the building component on which they are applied; delay the effects of outdoor climatic elements and decrease their amplitude to transfer to indoors. PCMs can store thermal energy as latent heat [5,6,7]. Additionally, latent heat storage capacity of PCMs per zone mass is higher than sensible heat. Since PCM's temperature remains almost constant during the phase transition (energy storage process) of the building component they are applied on, it is suitable for energy storage and recovery applications. Melting temperature value should be close to indoor temperature value when selecting PCMs [8]. Solidification temperature of PCMs should be a few degrees lower than indoor temperature which is necessary to balance indoor thermal comfort conditions [9]. These materials use the principle of preventing heat losses on the building components they are applied on.

Performances of PCMs can vary depending on different climate regions. PCMs have a reducing effect on heating energy consumption in winter and cooling energy consumption in summer using the energy stored during the day and released later. These materials are generally used as a passive strategy to reduce energy loads in cooling required regions [9]. However, PCMs were demonstrated to have a significant effect on the reduction of heating loads in previous studies [10,11].

PCMs are mostly applied by integrating into plaster, filler, concrete and other building materials or as a surface of blocks among building component layers [6]. With effective use of this material, heat transfer through building envelopes can be controlled to reduce energy loads.

Method

In this study, several alternatives for building envelopes were developed for the zone included in the study to reduce heating and cooling energy consumption. These alternatives were evaluated for a building with a single zone in Diyarbakır and Erzurum. Energy performance of the building envelop surface on which Phase Change Materials were applied was comparatively evaluated with the simulation tool EnergyPlus™ version 9.0.1.

Determining Building Related Variables

In this study energy consumptions of a building with a single zone were evaluated with PCM alternatives with varying thicknesses in different climate regions and with façades with different transparency ratios. Based on these, building component alternatives were developed to achieve minimum annual heating, cooling and total energy consumption in Diyarbakır, a representative city in the hot dry climatic region of Turkey and in Erzurum, a representative city in the cold climatic region of Turkey. Thus, PCM performance was evaluated for heating and cooling energy consumption in Diyarbakır and Erzurum.

In accordance with the standard TS-825 "Thermal insulation requirements for buildings", total heat transfer coefficient values which should be achieved on building envelopes in Diyarbakır (region 2) and in Erzurum (region 5) were determined based on the upper limits recommended by the regulation and are shown in **Table 1**.

Table 1. *U values recommended for regions [12].*

	U_{WALL} (W/m²K)	U_{ROOF} (W/m²K)	U_{FLOOR} (W/m²K)	U_{WINDOW} (W/m²K)
Reg. 2	0.57	0.38	0.57	1.8
Reg. 5	0.36	0.21	0.36	1.8

Typical meteorological year (TMY) file type was used as climate data in this study. A typical meteorological year (TMY) is a set of meteorological data with data values for every hour in a year for a given geographical location. According to the selected TMY files; The monthly average outdoor temperature variation in both provinces is shown in **Figure 1**.

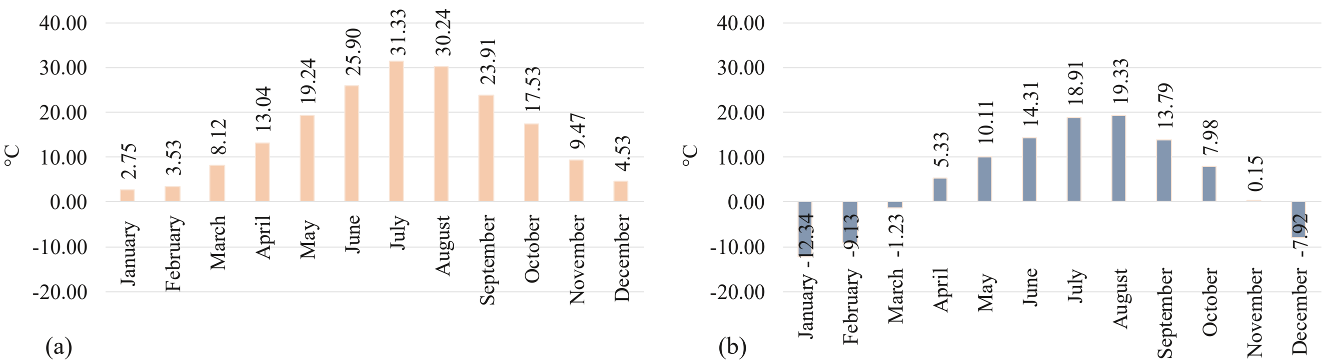


Figure 1. Monthly average outdoor temperature variation for Diyarbakır(a) and Erzurum(b).

The study was conducted on a square building with a single zone and flat roof and with a building footprint of 10 × 10 meters on a level ground. Different transparency ratios were used for the south façade of the zone to have a comparative evaluation. These ratios for the south façade were 10%, 20%, 30%, 40%, 50%, 60% while for other façades only 0% was used. The zone evaluated is shown in the **Figure 2**.

Total heat transfer coefficient of transparent element was taken as U = 1.5 W/m²K in all calculations in accordance with the standard TS-825 "Thermal insulation requirements for buildings". Solar heat gain coefficient of the transparent component was 0.6 and visible transmittance was 0.7. The building envelope layering details are shown in **Table 3**.

Determining the variables of calculation

The zone selected for the evaluation was assumed to be used for 24 hours. Thermal comfort value for indoor temperature during the year was taken as 20°C in the heating period and 26°C in the cooling period. The hourly outdoor temperature variation for the 21st day of each month is shown in **Figure 3** for both provinces. Based on this, it is seen that the heating system will operate for a while during the day even in spring time. Other variables included in the calculation are shown in **Table 4**.

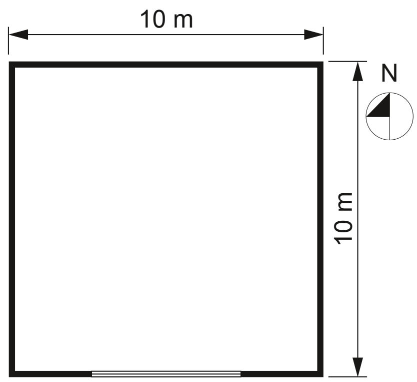


Figure 2. Zone evaluated in the study.

Table 3. *Building Envelope Layering Details of the zone in accordance with the standard TS-825.*

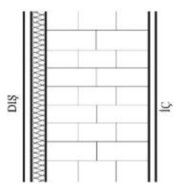
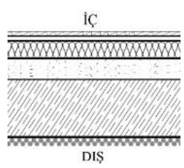
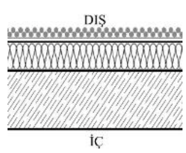
Opaque Components		Materials	λ (W/mK)	Diyarbakır (D) Thickness(m)	U (W/m² K)	Erzurum (E) Thickness(m)	U (W/m² K)
Exterior Wall		1. Lime Mortar 2. XPS Extruded Polystyrene 3. Brick 4. Gypsum Plastering	0.8 0.034 0.72 0.4	0.01 0.045 0.19 0.01	0.564	0.02 0.075 0.19 0.01	0.345
Ground Floor		1. Timber Flooring 2. Floor/Roof Screed 3. XPS Extruded Polystyrene 4. Cast Concrete (Light) 5. Cast Concrete	0.14 0.41 0.034 1.9 1.13	0.03 0.03 0.04 0.05 0.12	0.569	0.03 0.03 0.075 0.05 0.12	0.359
Roof		1. Miscel Mater 2. Floor/Roof Screed 3. XPS Extruded Polystyrene 4. Cast Concrete 5. Gypsum Plastering	1.3 0.41 0.034 1.13 0.4	0.08 0.03 0.075 0.15 0.01	0.379	0.08 0.03 0.15 0.15 0.01	0.205

Table 4. Other variables included in the calculation.

1	Illuminance level per square meter in the zone	8 W/m^2
2	Infiltration rate (according to the ASHRAE Standard 55 and BEP-TR Calculation Method for Building Energy Performance).	0.5 h^{-1} [12].
3	Night Ventilation	is neglected
4	Natural Ventilation	Closed
5	Mechanical Ventilation	Mechanical ventilation was assumed to be activated only when indoor air temperature rises above the thermal comfort value (26°C for cooling period).
6	Occupant Intensity (TUIK 2017)	4 persons [13].
7	Equipment Use	Daily usage density was determined. [12,14].
8	Climate data for 2 and 5. degree day regions	2009 Meteonorm climate data files were used.
9	Calculation Algorithm	Finite differences calculation method
10	Selected PCM types	SPE26E for Diyarbakır - BioPCM/M27/Q21 for Erzurum

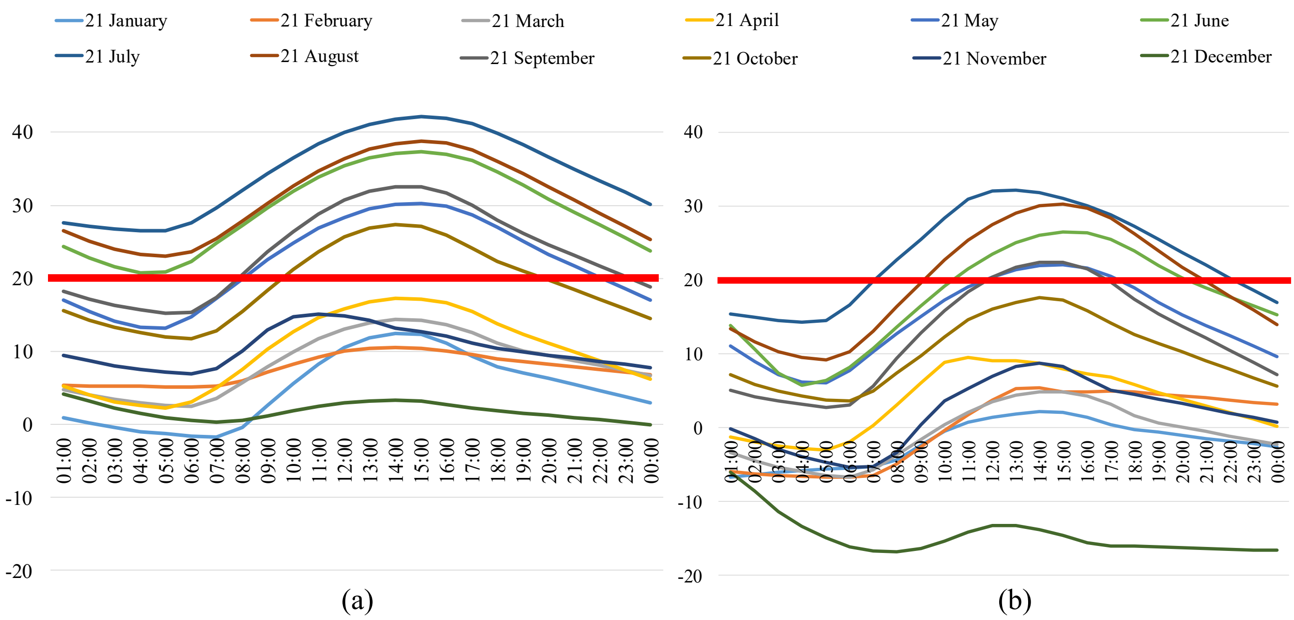


Figure 3. Hourly outdoor temperature variation for the 21st day of each month for Diyarbakır(a) and Erzurum(b).

PCM types shown in **Table 4** were entered in the EnergyPlus™ 9.0.1 simulation program. Performance evaluation of the surfaces on which PCM was applied was repeated for different alternatives developed with these materials. When designing alternatives, PCM material was considered as a separate layer like other materials. Melting temperature of the PCM selected in the study is a determining factor during phase change. Based on previous studies, indoor temperature value close to PCM melting temperature allows PCMs to show a better performance [5,6]. Therefore, in this study, different PCM types were used in Erzurum and Diyarbakır which have different climate characteristics. Material properties are shown in **Table 5**.

Table 5. Thermophysical properties of the PCM used in the study.

Thermophysical properties	SP26E	BioPCM/M27/Q21
Sensible Heat	2 000 J/kg-K	1 970
Melting Temperature	26°C	21°C
Conductivity	0.9 W/mK	0.2
Density	1 500 Kg/m^3	235

Determining the position and thickness of phase change materials on a building envelope

Previous studies on the subject reported that application of PCMs on the inner surface of the insulation material led to a better performance related to reduction in energy consumptions [11]. Therefore, PCM was applied on the inner surface of the insulation material in this study. To evaluate heating and cooling energy consumption performance of the building envelope on which PCM was applied;

- Building envelope alternative with no PCM and
- Building envelope alternatives with 3 cm, 4 cm, 5 cm PCM were developed (**Table 6**).

PCM thickness alternatives created for the zone were evaluated by applying on all façades of the building envelope (exterior walls, roof, internal floor).

In order to make a comparative evaluation for the zone; alternatives with and without PCM were combined with varying transparency ratios of 10%, 20%, 30%, 40%, 50%, 60%.

Table 6. *U values of the building envelope if different PCM thicknesses are applied.*

	PCM thicknesses	U_{WALL} (W/m^2K)	U_{FLOOR} (W/m^2K)	U_{ROOF} (W/m^2K)
Erzurum	3 cm	0.328	0.34	0.199
	4 cm	0.323	0.335	0.197
	5 cm	0.318	0.329	0.195
Diyarbakır	3 cm	0.553	0.558	0.375
	4 cm	0.55	0.555	0.373
	5 cm	0.546	0.551	0.372

Results

Annual heating and total energy consumption values in the zone, which changed with the changes in the façade transparency ratios and PCM thickness were calculated for Diyarbakır and Erzurum. Heating and cooling energy consumptions in Diyarbakır and Erzurum are shown in **Table** 7.

When we look at the heating and cooling energy consumptions of the cities; the alternative with 5 cm PCM was the alternative with the lowest consumption in both cities, which was in direct proportion with the increasing PCM thickness. Additionally, as the transparency ratio increased, heating energy consumption for the two cities decreased and cooling energy consumption increased.

Evaluating the heating and cooling energy consumptions of the zone in the alternatives developed for the study the following can be reported:

For the Diyarbakır climate: compared to the alternative without PCM, the alternative with 5 cm PCM reduced the heating energy consumption of the zone by 15.56% with 60% transparency ratio, 15.22% with 50% transparency ratio, 14.89% with 40% transparency ratio, 14.63% with 30% transparency ratio, 14.09% with 20% transparency ratio and 13.69% with 10% transparency ratio.

Compared to the alternative without PCM, the alternative with 5 cm PCM reduced the cooling energy consumption of the zone by 31.86% with 60% transparency ratio, 33.58% with 50% transparency ratio, 34.88% with 40% transparency ratio, 33.87% with 30% transparency ratio, 36.79% with 20% transparency ratio and 36.82% with 10% transparency ratio.

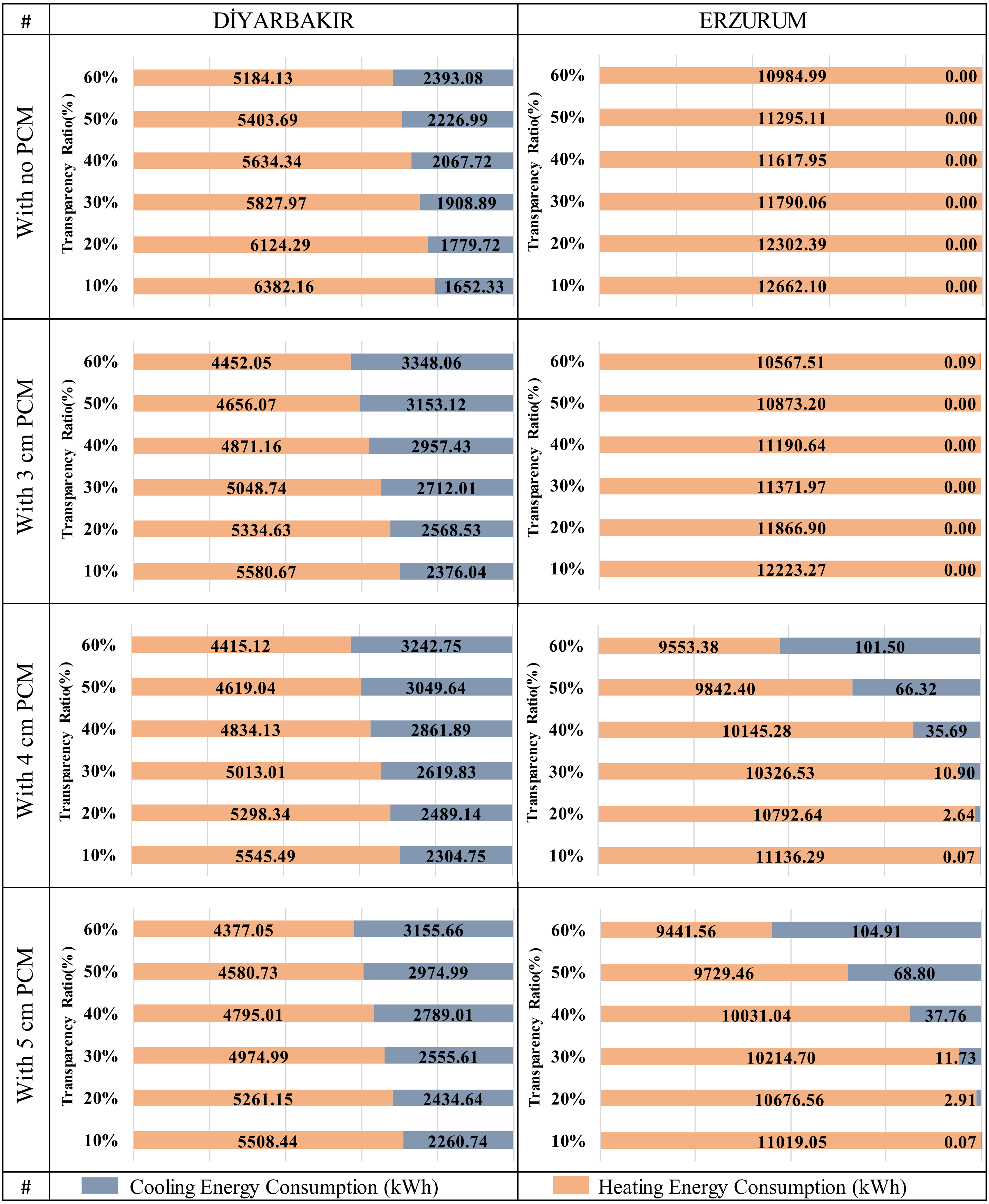
For the Erzurum climate: compared to the alternative with no PCM, the alternative with 5 cm PCM reduced the heating energy consumption of the zone by 14.05% with 60% transparency ratio, 13.86% with 50% transparency ratio, 13.65% with 40% transparency ratio, 13.36% with 30% transparency ratio, 13.21% with 20% transparency ratio and 12.97% with 10% transparency ratio.

Compared to the alternative with no PCM, the alternative with 5 cm PCM had the highest increase in the cooling energy consumption of the building. No cooling energy consumption was observed in the alternative with no PCM. In the alternative with 3 cm PCM and 60% transparency ratio and in the alternatives with 4 and 5 cm PCM with 10%, 20%, 30%, 40%, 50%, 60% transparency ratios, cooling energy was consumed.

Discussion

When today's energy consumption rates are analysed, it is seen that energy used in buildings has a higher percentage. This study comparatively evaluated the contribution of the application of PCMs with different

Table 7. *The demonstration of cooling, heating loads and total loads calculated for different PCM thicknesses in Diyarbakır and Erzurum.*



thicknesses on the building envelope to the heating and cooling energy performance of the building depending on different transparency ratios of façades. The findings of the study are summarized below;

- When correct design decisions are taken, PCM seems to contribute to the reduction of total annual energy consumption in buildings.
- The best alternative with PCM for the reduction of heating energy consumption is the alternative with 5 cm PCM.
- For cooling energy consumption; the best alternative for Diyarbakır was the alternative with no PCM.
- In the alternatives with PCM, increase in the thickness of the material leads to a reduction in cooling energy consumption. However, it is still higher than the alternative with no PCM. Because PCM may have shown a thermal insulation material performance by surrounding the shell as an additional layer.
- For Erzurum, increase in the PCM thickness leads to an increase in the cooling energy consumption.
- When all transparency ratios used for PCM were compared for both cities, increasing transparency ratio decreased heating energy consumption but increased cooling energy consumption.

Based on this study and its findings; further studies on evaluation of PCM application according to the orientation of the zone in the building and variation of PCM applications in order to balance energy loads in the zone can be recommended. ■

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