Evaluation of the Performance of Phase Change Materials in relation to Balanced Distribution of Heating Energy Cost in Residential Buildings

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A significant part of the total energy consumed in Turkey is used to heat residential buildings. Various measures have been made mandatory by regulation to reduce energy consumption for heating purposes and achieve a balanced cost distribution. The heat cost allocator system, one of the mandatory measures has been implemented in residential buildings since May 2, 2012. Since different indoor temperatures are observed in zones in buildings when heat cost allocator is used, heat is transferred through inner walls. Phase change materials which reduces heat transfer with the latent heat storage (LHS) system and with their low thermal conductivity can possibly reduce the fluctuations of the indoor air temperature of the zones and create a balanced heating energy cost [1][2]. In this study, application of phase change materials (PCM) on inner walls, external walls, floors and roof of a zone was evaluated using modelling and simulation.

Keywords: Phase change materials (PCM), heat cost allocators, heating energy saving, envelope, directing, zone organization.

Eighty-two per cent of the energy consumed in buildings is used for heating. Therefore, given our dependency to export energy resources, reducing the energy spent for heating purposes in buildings has become a necessity. Reducing heating energy expenditure in buildings is possible by making correct decisions for the design variables affecting the heating energy load of the building [3]. The most important design variable that directly affects thermal comfort and energy consumption is the building envelope. The objective of using heat cost allocator in Turkey is to ensure that users pay for only the amount of heating energy they actually consume. However, due to difference in directions and locations of zones, energy consumed in each zone differ significantly from others. As a result of this, heat is transferred between zones that

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have different indoor temperatures and unbalanced heating energy consumptions become inevitable[4]. Thermal energy storage capacity of PCMs is used to reduce energy consumption for heating in buildings. Latent heat is the heat that the material receives from or releases to the environment during phase change [5]. PCMs are materials that store thermal energy as latent heat.PCM storage systems allow conservation of heat on the surfaces they are applied and therefore they are used in buildings for their high energy storage capacities.

In this study heating energy generated by applying PCMs on inner walls, external walls, roofs and floors was calculated using a simulation program and analyzed according to different locations of apartments.

Properties of Phase Change Materials

We often see heat storage systems in traditional architecture together with the concept "thermal mass". Thermal mass absorbs heat all day, stores and release the heat to the interior by delaying the effects of outdoor climatic elements and reducing their amplitude thus preventing over heating of the interior spaces [2]. Time lag and decrement factor refer to the heat storage and insulation capacity of a building component. PCM can be defined as contemporary version of thermal mass. PCMs show varying performances depending on to the climate types [3]. Thermal energy which PCMs store day and night and release to the interiors is known to have reducing effect on not only heating energy consumption in winter but also cooling energy consumption in summer. Based on the studies, PCMs are known to show the best results in areas where temperature between day and night is bigger. [6]. In hot climatic regions, with the heat they store during night, PCMs can optimize indoor temperature. Thus, it reduces cooling requirement in hot dry climatic regions. However, in cold climatic regions their working principle is to prevent a decrease in indoor temperature, therefore, PCMs tend to reduce the energy spent for heating in cold climatic regions [5][7]. Thermal energy storage methods are classified into two groups, the first being sensible heat and the other is latent heat. Sensible heat is the storage of energy by using the heat storage capacity of a material, either solid or liquid. By increasing the temperature of the heat storage material, the energy is stored as sensible heat. The ambient temperature changes during sensible heat storage. Latent heat is the heat that the material receives from or release to the environment during phase change. Storage capacity required for latent heat storage methods is smaller than that required for sensible heat [3][8].

Heat storage capacity of PCMs per unit mass or unit volume is higher than the storage capacity of sensible heat storage materials. Since PCM's temperature remains almost constant during the energy storage process, it is quite suitable for energy storage and recovery applications at a constant temperature [5] [9].

Another thermophysical property of PCMs is their melting and solidifying temperature. Melting temperature quantifies the point at which a material liquefies (becomes completely liquid). The most suitable melting temperature for PCMs is the temperature which is the closest to the indoor temperature. Solidifying temperature quantifies the point at which a material solidifies (becomes completely solid). Based on the findings of the applications, the most suitable PCM is the one which has the melting temperature which is the closest to the indoor temperature [4] [10].

Evaluation of the performance of Phase Change Materials in relation to balanced distribution of heating energy use in residential buildings

In this study, several options for building envelopes were developed that can be used to reduce and balance heating energy consumption. These options were applied on a building in Istanbul using Design Builder program. Design Builder is a user friendly visual interface program that uses Energy Plus program as the simulation motor, which is an integrated simulation program.

Determination of Building Specific Variables

Heating energy efficiency of phase change materials was evaluated on a three-storey building with 12 zones (4 zones on each floor) and a flat roof with a floor area of 10x40 metres on a flat land in Istanbul. The transparency ratio of the building on south and north façades was accepted as 45%. The zones in which the evaluation is carried out are shown in **Figure 1**.

In order to evaluate PCM performance, building envelope alternatives did not have PCM in the first stage whereas PCM was applied in the second stage. The

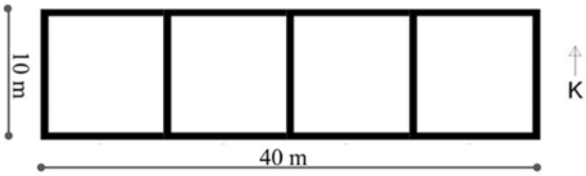


Figure 1. 10x40 m building used in the evaluation study.

following alternatives were created based on the location of the PCM applications. In the alternatives where PCMs are applied on inner walls and inner floors, they are applied on both sides of the building components.

A1. Application without PCM
A2. PCM application on exterior walls, ground floor and roof
A3. PCM application on external walls, inner walls, ground floor and roof
A4. PCM application on external walls, inner floors, ground floor, and roof
A5. PCM application on external walls, inner walls, inner floors, roof and ground floor

The building envelope layering details are shown in **Table 1**.

Calculation Variables

In this study the advanced modelling tool, Design Builder 5.0.3.007 application software was used to evaluate energy efficiency of phase change materials by applying them on building components. Design Builder is a dynamic thermal simulation software that uses "finite difference method". Thus, it is possible to analyse thermal performance of phase change materials. In calculations, the comfort value for indoor air temperature was accepted as 21°C for heating and 19°C as the lower limit value to turn on the heating system; as 26°C for cooling and 28°C as the upper limit value to turn on the cooling system.

Calculation of Heating and Cooling Loads for Different Zones with Different Building Envelope Alternatives

In the first stage of the calculations PCM was not used on any wall (without PCM-A1). In other alternatives with PCM, 3 cm PCM was used on all exterior walls, inner walls, floors and roof. Based on the calculations, heating energy loads were compared with each other to compare energy efficiency of different zones in the building.

When energy consumptions for heating were evaluated, heating energy consumption was lower on the ground floor and first floor in zone 2, zone 3, zone 6 and zone 7; and higher in Zone 9 and Zone 12 on the second floor in all alternatives. The alternative 1 without any PCM application had the highest heating energy expenditure in all zones. When Alternative 2 with PCM application on the whole building envelope is used, the resultant heating energy consumption was always lower than the alternative without any PCM application (alternative 1). However, when PCM was applied on floors and inner walls and other alternatives with varying PCM applications are compared, the lowest heating energy consumption was in zone 1, zone 2, zone 3, zone 4, zone 5, zone 6, zone 7 and zone 8 in Alternative 5. The lowest heating energy consumption in Zone 9, zone 10, zone 11 and zone 12 was achieved in Alternative 3. When PCM was applied only on inner walls i.e. when heat loss between horizontal zones was prevented, (alternative 3) heating energy consumption decreased in zone 9, zone 10, zone 11 and zone 12 on the upper floors but increased in other zones (zone 1 to zone 8) and the lowest heating energy consumption was in zone 2 and zone 3. When PCM was applied only on inner floors i.e. when heat loss between vertical zones was prevented, (alternative 4) heating energy consumption increased in zone 9, zone 10, zone 11 and zone 12 on the upper floors but decreased in other zones (zone 1 to zone 8) the lowest heating energy consumption was in zone 6 and zone 7. When PCM was applied both on the entire building envelope and on inner floors and inner walls (alternative 5), heating energy consumption increased in zone 9, zone 10, zone 11 and zone 12 on the second floor but minimum consumption was achieved in all other zones leading to most favourable conditions. Heating loads of all 12 zones in the building according to their locations are shown in **Figure 2**.

Heating, cooling and total energy consumptions for the entire building are shown in **Figure 3**; a,b and **Figure 4**.

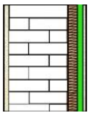
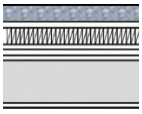
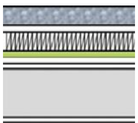
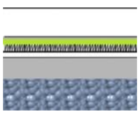
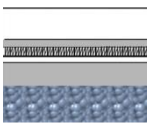
The best result for reduced heating energy consumptions in the entire building was obtained in the alternative A5. The alternative A5 where the lowest heating energy was achieved showed 8.6% better performance than A1, 3.74% than A2, 4.14 than A3, 0.77% than A4.

The best result for reduced cooling energy consumptions in the entire building was obtained in the alternative A5. The alternative A5 where the lowest cooling energy was achieved showed 10.1% better performance than A1, 9.47% than A2, 10.48 than A3, 1.45% than A4.

The best result for reduced energy consumptions in the entire building was obtained in the alternative A5. The alternative A5 where the lowest total energy consumption was achieved showed 9.18% better performance than A1; 6.01% than A2, 6.66 than A3, 1.03% than A4.

In the entire building, the alternative A5 had the best results for both the heating and cooling periods.

Table 1. Layering details of the building envelope.

Without PCM	External Wall	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Gypsum Plastering XPS Extruded Polystyrene Brick Cement/Plaster/Mortar	0.02 0.04 0.24 0.01	0.72 0.034 0.72 0.4	1860 35 1920 1000
With PCM	External Wall	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Gypsum Plastering PCM/BioPCM® M51/Q21 XPS Extruded Polystyrene Brick Cement/Plaster/Mortar	0.02 0.03 0.04 0.24 0.01	0.72 0.2 0.034 0.72 0.4	1860 235/J/kg·K 1970 35 1920 1000
Without PCM	Inner Wall	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Gypsum Plastering Brick Gypsum Plastering	0.01 0.1 0.01	0.4 0.72 0.4	1000 1920 1000
With PCM	Inner Wall	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Gypsum Plastering PCM/BioPCM® M51/Q21 Brick PCM/BioPCM® M51/Q21 Gypsum Plastering	0.01 0.03 0.24 0.03 0.01	0.4 0.2 0.72 0.2 0.4	1000 235/J/kg·K 1970 1920 235/J/kg·K 1970 1000
Without PCM	Flat Roof	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Aggregate-sand-gravel Mastic Asphalt XPS Extruded Polystyrene Bitumen/ Felt Layer Polyethylene Concrete Gypsum Plastering	0.06 0.002 0.06 0.003 0.003 0.15 0.02	1.30 0.19 0.034 0.50 0.33 1.13 0.4	2240 950 35 1700 920 2000 1000
With PCM	Flat Roof	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Aggregate-sand-gravel Mastic Asphalt XPS Extruded Polystyrene PCM/BioPCM® M51/Q21 Bitumen/ Felt Layer Polyethylene Concrete Gypsum Plastering	0.06 0.002 0.06 0.03 0.003 0.003 0.15 0.02	1.30 0.19 0.034 235 0.50 0.33 1.13 0.4	2240 950 35 235 / J/kg·K 1970 1700 920 2000 1000
Without PCM	Ground Floor	d(m)	Conductivity(W/mK)	Density (kg/m³)
	Gravel Concrete Bitumen/ Felt Layer XPS Extruded Polystyrene Gypsum Timber Cover	0.15 0.10 0.006 0.04 0.03 0.14	0.36 1.4 0.5 0.034 1.13 0.14	1840 2100 1700 35 2000 650
With PCM	Ground Floor	d(m)	Conductivity(W/mK)	Density (kg/m³
	Gravel Concrete Bitumen/ Felt Layer PCM/BioPCM® M51/Q21 XPS Extruded Polystyrene Gypsum Timber Flooring	0.15 0.10 0.006 0.03 0.04 0.03 0.14	0.36 1.4 0.5 235 0.034 1.13 0.14	1840 2100 1700 235/J/kg·K 1970 35 2000 650
Without PCM	Inner floor	d(m)	Conductivity(W/mK)	Density(kg/m³)
	Plaster Concrete Plaster	0.01 0.1 0.01	0.4 1.13 0.4	1000 2000 1000
With PCM	Inner floor	d(m)	Conductivity(W/mK)	Density(kg/m³)
	Plaster PCM/BioPCM® M51/Q21 Concrete PCM/BioPCM® M51/Q21 Plaster	0.01 0.03 0.1 0.03 0.01	0.4 235 1.13 235 0.4	1000 235/J/kg·K 1970 2000 235/J/kg·K 1970 1000

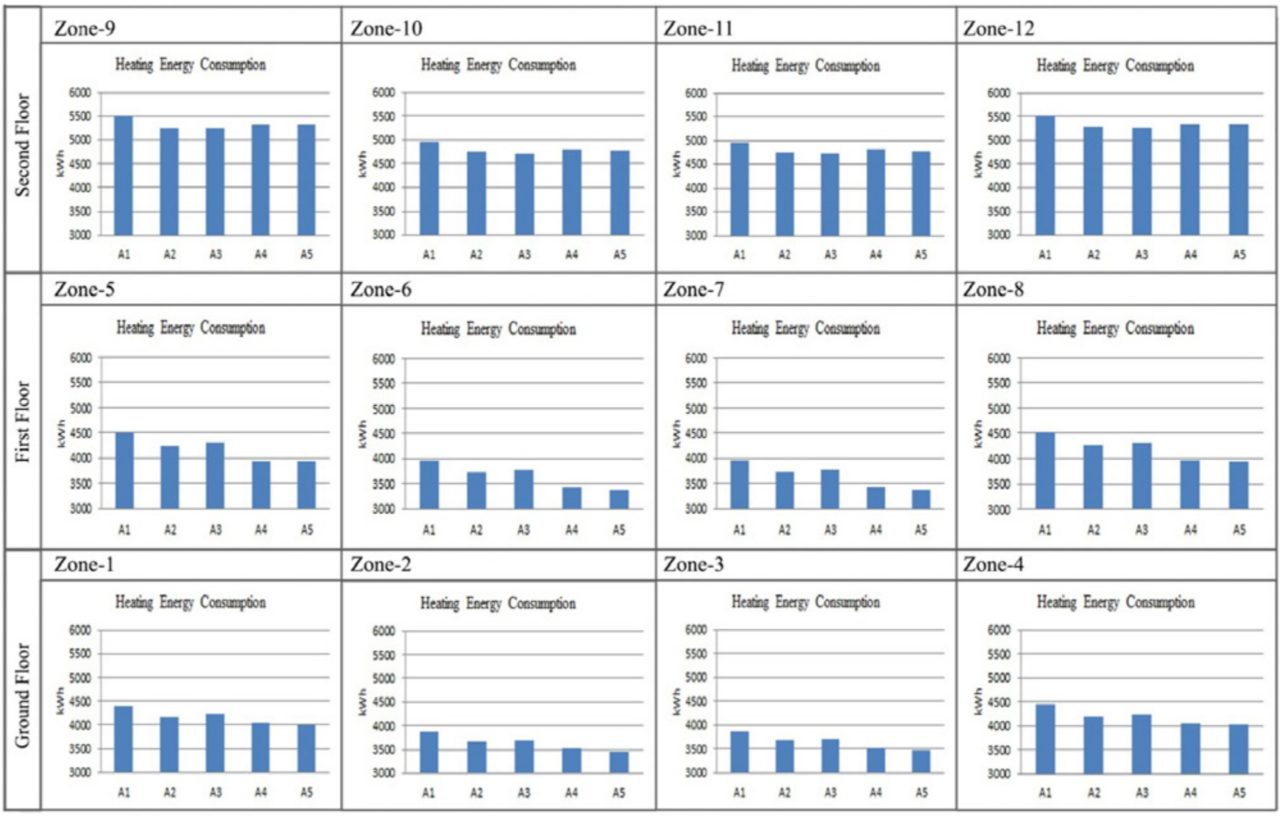
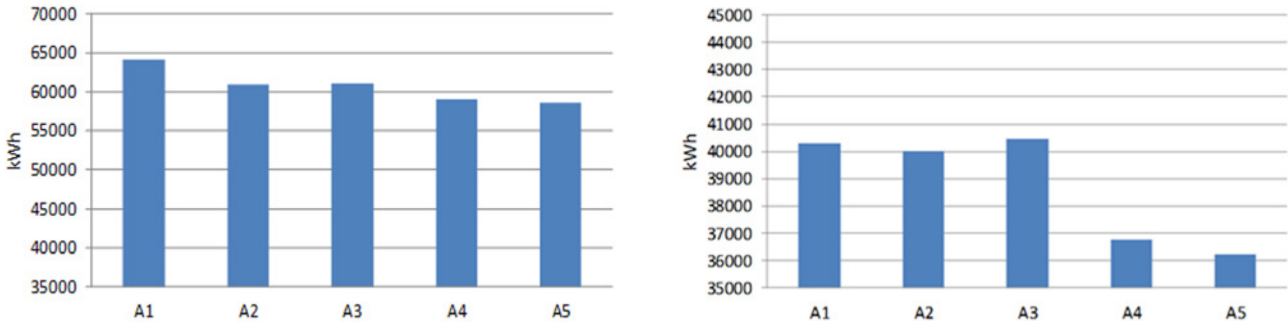


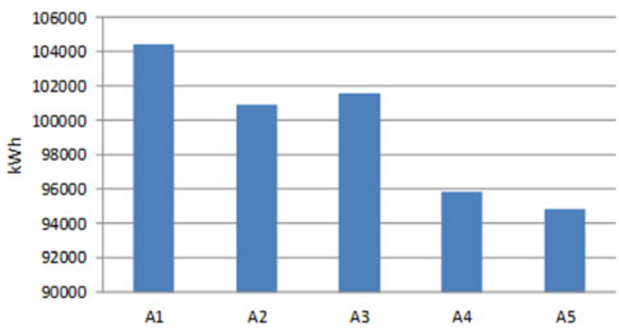
Figure 2. Heating energy consumption of different zones in the building



a) Heating energy consumptions

b) Cooling energy consumptions

Figure 3. Variations in annual energy consumption in the building with different building envelope applications.



Total energy consumption

Figure 4. Variations in annual total energy consumption in the building with different building envelope applications.

Conclusion

When analysing the current statistics of energy consumption today the energy used in buildings has a significant share in the total energy consumption. This situation should be evaluated both in relation to energy consumption costs and eco-friendly building design criteria.

- In this study, Phase Change Materials which are considered to be contemporary alternatives to thermal mass which is the conventional heat storage system were evaluated. Based on the findings of the study, the contribution of the use of PCMs in different building components to the building's energy consumption performance was comparatively evaluated. When correct decisions about design are taken, PCM seems to contribute to the reduction of total annual energy consumption in buildings. The findings of the study are summarized below:
- The reason why some zones have minimum energy consumption is the fact that other zones with less favourable conditions surrounding them consume more energy which they cannot control due to their positions and larger external walls.
- The zone with minimum energy consumption cannot possibly have minimum energy consumption without the apartment with highest energy consumption. In other words, the zone with the best conditions can only have these best conditions as a result of the existing conditions of other zones. Therefore, energy consumption values in the zones as a result of the use of heat cost allocators are not the result of users' preferences but due to the positions of the zones in the building.
- When we try to balance the difference in heating energy consumption of zones due to the use of heat cost allocators, we saw that single type of application could not provide balanced comfort conditions in all apartments and different measures were required for different zones.
- When PCM was applied on exterior walls, inner walls, inner floors, ground floor and roof (A5) low energy consumption was achieved both separately in every zone and in the building as a whole. Therefore, it can be suggested that PCM applications can decrease unbalanced heating energy consumptions that occur when heat cost allocators are used.
- If the heat loss that occurs when PCM is applied on inner floors and inner walls is evaluated specifically for each zone, zone specific improvement alternatives can be created depending on the positions and external walls of zones.
- PCM's contribution consumption performance was observed to be higher in cooling period. Therefore, for PCM applications, the climatic region (cooling priority / heating priority) in which the building is in should be taken into consideration.

For future studies; PCM performance evaluations can be diversified by using different design criteria and PCM's areas of use and properties can be improved. Thus, a variety of solutions can be created to reduce energy consumption. ■

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