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Investigation of energy saving in building by using phase-change materials (PCM)

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ABSTRACT

The increase of human population has led to the augmentation of buildings' numbers and high energy consumption. About 30% of the world's energy consumption is in the heating and cooling sector of residential buildings. Due to the increase in energy consumption in the building industry, energy management in this sector would be very significant and it is necessary to provide effective solutions to reduce energy consumption by avoiding waste and reducing the cost of construction and cost of utilization of buildings. One of the most effective method for reducing energy consumption is the use of phase-change materials for energy storage. Their performance is such that with increasing the temperature, their phase is changed and they store the heat energy and release this energy by reducing the temperature. In this research, a geometry in the climate of Tehran is simulated by using the Energy Plus and the Open Studio software. In the present study, four phase change materials (PCM) with different thermo-physical properties were investigated. The results indicated that each of the four utilized PCMs would reduce energy consumption, however, the highest reduction in the energy consumption would be obtained when the PCM 22 is used. Which is 50.75% for cooling and 45.35% for heating purposes, and the amount of energy consumption in buildings can be minimized by increasing the thickness of PCMs.

1. INTRODUCTION

By considering the increasing the energy demand and the limitation of fossil fuels as an end-of-life source and the environmental pollution, the utilization of renewable energy sources is increasingly required [1–4]. One of the energy that it is increasingly used for is the solar energy [5–9]. The use of phase-change materials to store thermal energy is an important aspect of energy management contributed to the energy crises in the recent years since they can store energy in both latent and tangential heat [10]. Energy is considered to be the most important aspect of the human life. Human history and civilization have been based on inventions and discoveries to convert different energies into each other [11]. The rise of human population has led to the augmentation of buildings' numbers and high energy consumption which more than 30% of the world's energy consumption is in the heating and cooling sector of residential buildings [12].

Due to the increase of energy consumption in the building industry, energy management in this sector is exceptionally significant and it is necessary to provide effective solutions to reduce energy consumption by avoiding waste and reducing the cost of construction and cost of utilization of buildings [13]. In recent years, the concept of reducing energy consumption in the building has been increasingly considered by researchers for reasons such as economic benefits and long-term environmental sustainability [14].

2. M OPTIMIZATION OF THE SUPPLY AND DEMAND OF ENERGY IN THE BUILDING SECTOR

T The rational use of energy is at the core issue of the non-fossil energy countries and has led them to apply all of their considerations to the issue of optimizing energy consumption in one of the main sectors of energy consumption named residential buildings. So, for many years, countries such as Germany, Sweden, Italy, and Britain have specific rules for building and applying heat insulation, improving heating and cooling, and building structure in order to optimize the energy consumption [15]. The building sector in each country accounts for more than a third of the energy consumption which values a total of six billion dollars annually. As the result, the issue of the limitations and lack of energy resources in the world are no longer ignored by anyone, and thus, this study is struggling to address this problem and to improve project management in order to maintain the country's energy and capital [16].

2.1 Phase change materials

One of the most important methods for storing heat energy is phase change materials that when necessary, change the phase, store energy in different shapes and, when necessary, release it [17]. The phase change materials absorb and release the heat in the condition of approximately constant temperature. These materials approximately store 5 to 14 times more heat per unit of volume than other materials such as water [18].

Materials in nature exist in three phases such as liquid, solid, and gas. If a substance changes from one phase to another, it absorbs or releases heat that is called the latent heat. For example, a solid, after warming up to its melting point, treats as an absorber of a high volume of energy (called melting heat) and changes its phase from solid to liquid. Phase change materials have the ability to change their phase at a specific temperature range. It means that they maintain their temperature during the process of changing the phase. In fact, the method of working these materials to store heat energy is to warm up in parallel with the environment during the warm-up process of the environment until it reaches its melting point (phase change) [19]. After reaching this temperature, despite the fact that the temperature of the environment continues to increase, the temperature of these materials and of course the surrounding environment remains constant and resists the temperature rise due to the phase change [20].

2.2 PCM properties

The properties of a PCM can be mentioned based on three views, which are:

- Thermodynamic view: A PCM, in thermodynamic view, should have a suitable phase change temperature, latent heat, specific heat capacity, density, and high thermal conductivity. Also, its volume variation during the phase change should be low and the PCM freezes at the melting temperature.
- Chemical view: From a chemical view, a PCM should be stable, non-fatal, non-toxic, non-flammable and non-explosive. Also, it should be compatible with the surrounding materials, and the melting and freezing cycles should be performed complete and there is no phase separation.
- Economic view: based on the economic view, a PCM should be affordable and available [17].

2.2.1 PCM categories

A large number of existing phase change materials can be classified into three broad categories: Organic, mineral (inorganic) and eutectic which are available at any given temperature and are shown in Fig. 1 [21].

- Organic PCMs

Organic materials are most often classified as paraffinic and non-paraffinic materials. The advantages of the organic phase change materials can be mentioned as the required adhesion, chemical stability, non-reactivity, and the ability to regenerate. Nevertheless, their heat conductivity in solid phase is low.

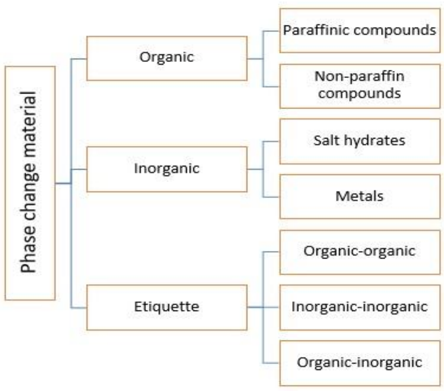

Figure 1. Tree graph of PCM categories

Melting point and latent melting heat of organic phase change materials which are commonly used in residential buildings applying radiation from the floor heating system are provided in Table 1.

Table 1. Organic phase change materials

combination	melting point(c)	Fusion heat(KJ/Kg)	combination	melting point(c)	Fusion heat(KJ/Kg)
C16-C18 Paraffin	(16)22-20	(16)152	Vinyl Stearic Acid	(20)29-27	(20)122
E600 Polyglycol	(17)22	(17)127.2	1-Tetradecanol	(18)38	(18)205
C13-C14 Paraffin	(14)24-22	(14)189	C16-C28 Paraffin	(14)44-42	(14)189
1-Dodecanol	(18)26	(18)200	C20-C33 Paraffin	(14)50-48	(14)189
C18 Paraffin	(19)27.5	(19)243.5	Paraffin wax	(17)64	(17)173.6

- Inorganic PCMs
- Inorganic materials

have high latent melting heat per mass units and high heat transfer. They also have a lower cost in comparison with organic and eutectic ones. They are non-Inflammable, however, they encounter the carrion on the condition of high cooling which affects the properties of their phase change. Fortunately, they are resistant to fire due to their non-In flammability.

Table 2. Inorganic phase change materials

combination	melting point(c)	Fusion heat(KJ/Kg)	combination	melting point(c)	Fusion heat(KJ/Kg)
KF-4H2O	(14)18.5	(14)231	Na2SO4.10H2O	(18)32.4	(18)254
Mn(NO3)2	(21)25.5	(22)125.5	Zn(NO3).6H2O	(17)36	(17)416.9
CaCL2.6H2O	(17)29	(17)190.8	Na2S2O3	(14)48	(14)201
LiNO3.3H2O	(6)30	(6)296	Na(CH3COO).3H2O	(6)58	(6)226

- Eutectic PCMs

Eutectic is a combination of two or more components with a minimum melting point. Each component is melted or frozen in a convergent manner, and a crystalline compound is formed. Limited research has been carried out regarding this concept [22].

Table 3. Eutectic phase change materials

combination	melting point(c)	Fusion heat(KJ/Kg)	combination	melting point(c)	Fusion heat(KJ/Kg)
66.6%CaCL2.6H2O+ 33.3%MgCL2.6H2O	(23)25	(23)127	61.5%Mg(NO3)2.6H2O+ 38.5%NH4NO3	(25)52	(25)125.5
48%CaCL2+4.3%NaCL+ 0.4%KCL+47.3%H2O	(23)26.8	(23)188	37%Urea+ 63.5%acetsmid	(14)53	
0.4%Ca(NO3)2.4H2O+ 33%Mg(NO3)2.6H2O	(14)30	(14)136	58.7%Mg(NO3).6H2O+ 41.3%MgCL2.6H2O	(25)59	(25)132.2
60%Na(CH3COO).3H2O+ 40%CO(NH2)2	(24)31.5	(24)226	67.1%Naphthalene+ 32.9%beNzoic acid	(25)67	(25)123.4

2.3 Utilization of phase change insulators to reduce the energy consumption in buildings

Phase change materials are one of the most efficient tools for storing thermal energy. Their performance is such that, with increasing temperature, they store the heat energy and release this energy by reducing the temperature. It is known that thermal energy can be stored in two ways: tangible heat and latent heat. But the energy stored through the latent heat associated with the phase change is more important because of the high density of thermal energy storage. Phase change materials are used in many cases such as medical applications, heating and cooling systems, thermal protection of food, textiles, and buildings.

It is worth noting that in recent years, the utilization of phase change materials in building applications has been so crucial for reducing energy consumption. The function of phase change materials in buildings is that by absorbing intrusive heat into the building, they melt. As the result, they save some intrusive thermal energy to the building's wall, thereby the space is prevented from warming up. Furthermore, their energy is released to the space by beginning to freeze at night. The effect of using phase change materials in the outer wall on indoor temperature is depicted in Fig. 2. As it can be seen, the range of outside air changes is reduced after passing through the wall and the time associated with the peak temperature is also altered, which leads to the lower energy consumption for cooling at the peak of consumption [23].

The purpose of using PCMs in the building can be enumerated as:

- The utilization of natural heat from the sun for cooling and heating
- The utilization of stored heat by the cooling and heating systems

In order to acquire the mentioned objectives by using PCMs, three ways can be provided:

1. Using PCMs in walls
2. Using PCMs in floors and ceilings
3. Utilization of PCMs in heating and cooling storages [24].

So, some research has been carried out in the recent years on the performance of PCMs in the heating and cooling systems in buildings and their advantages to reduce the energy consumption.

3. MODELING AND ANALYSING THE RESULTS

In this study, OpenScreen software was used to simulate the sample space. The schematic of the sample space is shown in Figure 3 while indicates the climate of the Mehrabad area in Tehran. Additionally, the comfort temperature of this space is considered to be 21 to 28℃.

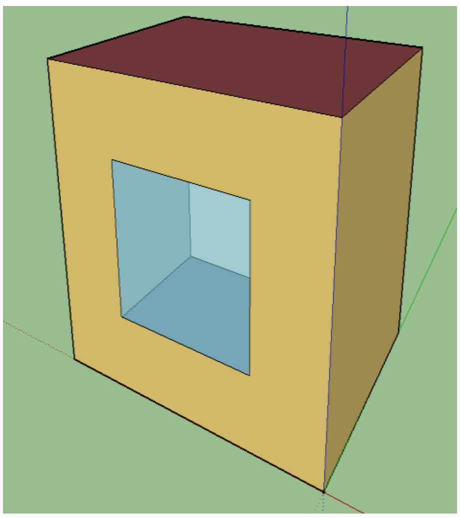

Figure 3. Schematic of the sample space

In this simulation, materials such as bricks and plaster were used which the information and physical properties of the utilized materials were extracted by the National Building Regulations of Iran [25] and are listed in Table 4.

Table 4. Thermodynamic properties and the material thickness applied in the simulation

kind	Thickness cm	Conducting w/m k	Density kg/m3	Specific Heat J/kg k
Bricks	10	1.1	1770	800
Plaster	2	0.75	1000	840

In order to reduce energy consumption, four types of phase change material have been investigated. The thermo-physical properties of the phase change materials are expressed in Table 5 [23].

Table 5. Thermo-physical properties of used PCMs in the simulated building

Insulation	melting point c	Density kg/m3	Conducting w/m .k	Specific Heat J/kg .k
PCM 22	22	11150	0.189	1700
PCM 26	22	950	0.35	840
PCM30	30	1620	0.81	1700
PCM34	34	1150	0.188	835

In this study, the energy consumption associated with the comfort temperature was initially obtained to simulate the sample space without using PCM by using Energy Plus software. So, the energy consumption for heating and cooling was depicted in Figure 4. Furthermore, the used materials for the wall from the outer layer to the inside are considered to be 10 centimetres of brick and 2 centimetres of plaster. Then, the simulation of the system by using PCM in the wall was carried out as the situations mentioned in Table 6. The layers of the materials used in the walls are in accordance with Table 6 and the graphs obtained from these simulations are shown below.

Table 6. Laying the wall of the building from the outside to the inside

State	Bricks	PCM	Bricks	Plaster
1 state (NO PCM)	5Cm	-	5Cm	2Cm
2 state (PCM 22)	5Cm	PCM 22	5Cm	2Cm
3 state (PCM 26)	5Cm	PCM 26	5Cm	2Cm
4 state (PCM 30)	5Cm	PCM 30	5Cm	2Cm
5 state (PCM 34)	5Cm	PCM 34	5Cm	2Cm

In Figure 4, which illustrates the energy consumption for cooling and heating, it can be seen that PCM 22 has a greater impact than other PCMs used in the simulation to reduce energy consumption (heating and cooling).

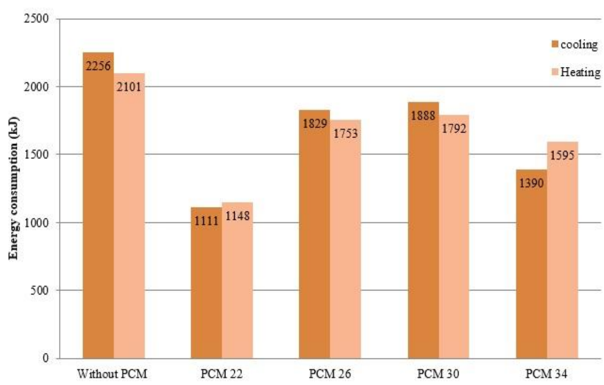

Figure 4. Energy consumption charts for cooling and heating

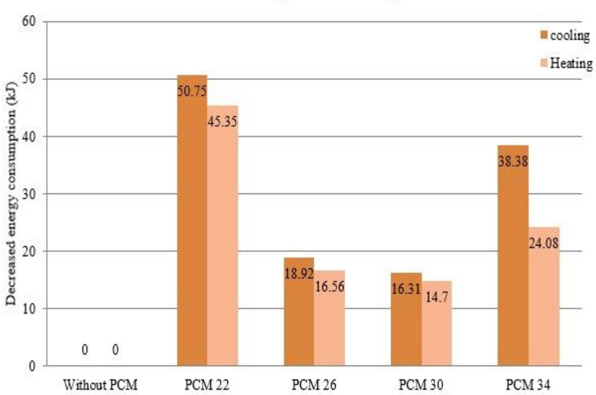

Figure 5. Percentage of energy consumption reduction in cooling and heating

As it is depicted In Figure 5, the most reduction in energy consumption in both heating and cooling sections is contributed to PCM 22, which is a reduction in the heating section of 45.35% and in the cooling sector of 50.75%. The percentage of energy consumption reduction in the cooling section is higher than that the heating section in PCM 22. The lowest reduction of energy consumption in both heating and cooling sections is related to PCM 30, which is 16.31% in cooling and 14.7% in the cooling section. The reduction of energy consumption in the cooling unit is greater than the heating section.

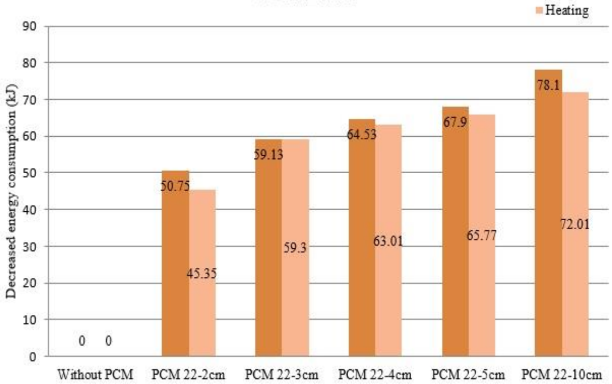

Figure 6. Percentage of energy consumption reduction associated with PCM 22 with different thicknesses

Furthermore, the percentage of energy consumption of PCM 22 with different thicknesses is shown in Figure 6, in which the highest percentage of energy consumption in the thickness of 10 cm can be achieved. Which in this thickness, the reduction of cooling energy is 78.1% and heating is 72.01%. Additionally, the lowest percentage of energy consumption in the thickness of 2 cm is observed, in which the reduction consumption in cooling section is 50.75 percent and in heating is 43.35 percent.

4. CONCLUSIONS

In this research, Energy Plus software was used to optimize energy consumption in a building in the climate of Tehran. This simulation was generally carried out in three modes. First, PCMs were not utilized in the simulation of the energy consumption and this quantity was obtained during one year for heating and cooling (comfort temperature) of the building. The results indicate that the amount of energy consumption of the building in the mentioned climate during one year is 2256 kJ for cooling and for 2101 kJ for heating. Then, in order to reduce energy consumption, four types of PCM (PCM22 - PCM26 - PCM30 - PCM34) were used with different temperatures and properties. So, with the help of Energy Plus software, the amount of energy consumption for these PCMs was achieved.

Regarding the results obtained from Energy Plus software, it can be concluded that each of the four used PCMs reduces the energy consumption, however, the maximum reduction of the energy consumption is contributed to PCM 22, which is 50.75% for the cooling and 43.35% for the heating purposes. PCM 22 which dedicated the most energy consumption reduction in both cooling and heating modes was used in the simulation with different thicknesses. As indicated in the results, it can be concluded that by increasing the thickness of the PCM, the amount of energy consumption in the building can be minimized.

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