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Investigation of Thermal Performance of 3D Printing Integrated Phase Change Materials in Building Structure

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ABSTRACT

This paper aims to create an experimental building structure using 3D printing technology to reduce the interior temperature. Because of its sensitivity to high temperatures, particularly its low heat deflection temperature, and susceptibility to deterioration over time, the Polylactic acid (PLA) material has been preferred to print the layer. In this model, an effort was made to decrease the building's overall cooling load, which may result in a higher amount of ordinary power being required. For the study, a new model of the intended wall was developed and tested. The studies were carried out in two modes: the first without any PCM in the wall, and the second with an additional new model of PCM 3D-printing layer within the wall. The test results demonstrated that the PCM 3D-printing layer inside the wall building lowered the temperature of the outer wall surface, the inner wall surface, and subsequently the building temperature of the indoor area to a huge amount. The achievements are in the percentage peak temperature reduction of 9.8% for the wall's outer surface, 22.6% of the inner wall surface, and 13.4% of the room temperature. With the help of the PCM 3D-printing layer, the peak indoor temperature was decreased by 5°C.

1. INTRODUCTION

The continuous rapid growth of the world's economy and the population is resulting in significant increases in global energy consumption and demand, which is triggering severe environmental consequences [1, 2]. According to the International Energy Agency, primary energy output and carbon dioxide emissions have increased by 49% and 43%, respectively, during the previous two decades as a result of increased energy consumption [3]. Buildings consume approximately 40% of total energy output, which is derived primarily from traditional energy sources [4]. However, the ensuing environmental disaster has only just begun, with the construction sector's energy consumption expected to reach 50% of total by 2050, and demand for space cooling expected to quadruple during this time [3]. Currently, the energy excursion from renewable foundations and zero-energy construction attempts are the most vital research domains, and investigators are working tirelessly to make significant advancements in these areas [5, 6]. In contrast to conventional buildings, zero-energy buildings are self-sustaining energy-based structures. They meet their energy requirements primarily through solar technologies, such as solar water heating systems [7], solar-assisted technologies to generate water [8], solar PV panels to generate electricity [9, 10], and natural lighting, among other things. For buildings, on the other hand, the cooling load has become a key source of worry for all kinds of construction [11]. The total energy usage of the building increases from the use of air-conditioning units [12]. In recent years, solar-powered air conditioning systems have continuously been proposed as tools to improve thermal comfort while also saving electricity. Zhai and Wang [13] strongly recommend using energy from solar energy systems in communal buildings to save the significant amount of conservative energy required to remove heat gain from the structures. A recent study on solar-powered building cooling systems found that the use of solar power in building structures should meet the measure of minimizing the CO_2 emission to the atmosphere [14]. The use of appropriate thermal isolating materials in building construction, which reduces the total cooling load of the structures, may result in a reduction in the overall cost of the building's thermal comfort systems. Solar heat gain in buildings is caused by sun-exposed surfaces such as walls, doors, windows, and roofs. Vijayalakshmi et al. [15] studied the thermal characteristics of building wall components in the interior environment. The thermophysical qualities of the materials used in ceilings and walls may greatly impact the rate of heat transfer and, therefore, the space heating loads and space cooling in buildings. Putting different types of phase-shifting the storage material of latent heat together with standard construction materials can make structures that are better at keeping heat out [16, 17]. The phase change materials may be incorporated into any aspect of a building, like floors, roofs, and walls [18, 19]. Phase change materials are the materials of latent heat storage applied in diverse applications, including thermal storage for solar heater water [20], temperature control of solar PV panels [21], yield improvement in solar stills [22], and so on. Inorganic and organic phase-changing materials (PCMs) are the most widely used in different applications [23, 24]. According to research, using appropriate phase change materials in building components such as walls and roofs helps keep the inside of the building cooler by lowering its overall solar thermal performance [25, 26]. Voelker et al. [27] evaluated the influence of phase change materials on area temperature lowering. According to their conclusions, the temperature dropped by 4°C during peak hours when compared to a control area that did not include phase change material. Kuznik and Virgone [28] found that the wall covered with phase change material helped to keep the room's air temperature inside the comfort region by dropping the room's highest air temperature to 4.2°C. Jiang et al. [29] investigated the interior envelope's intrinsic performance, such as adjusting specific heat and managing indoor air temperature. They discovered that the best PCM specific heat system complemented inside envelope specific heat form. Mandilaras et al. [30] created a two-story average primary residence with phase change material walls. According to their studies, the amount of heat flux inside the wall increased during the late spring, early summer, and autumn. The time lag raised by about 100 minutes, and the decrement factor was decreased by 30%. Sá et al. [31] created the new composite building material with micro-encapsulated phase change material incorporated into plastering mortar. The peak temperature of the trapped air was reduced by 2.6°C when mixing phase change materials with mortar. Abdulhussein et al. [32] conducted an experiment using perforated brick walls and PCM. Compared to traditional building materials, PCM absorbs more heat, hence walls made with it prevent temperatures from increasing.

3D printing, also known as additive manufacturing, has a wide range of potential applications in the automotive, aircraft, architectural, metal and alloy, electrical, and biological industries [33, 34]. Some academics have looked at 3D printing for thermal insulation and energy conversion. According to Jafari et al. [35], the suggested 3D-printed wick will boost the heat transfer performance owing to its great permeability and capillary performance. The 3D printed lattice structure meets weight, heat transmission, mechanical, optical, acoustic, and other criteria for space applications. It will introduce unknown properties like thermal storage rate and comparable thermal conductivity. Much experimental and theoretical study is required to fully comprehend solid-liquid phase-change heat transfer in 3D printed lattice structures.

This research aims to decrease the cooling load of buildings by using proper wall design and a phase change material, which would decrease the building's interior temperature, improve thermal comfort, and reduce the thermal cooling load. The relevance of this research is that it studies the impact of merging a PCM with a new layer's wall. The design of the new layer of PCM requires 3D printing technology. The Polylactic acid (PLA) substance used to print the proposed model because of its sensitivity to high temperatures, particularly its low heat deflection temperature, and its susceptibility to deterioration over time. This investigation will assist the researcher in observing temperature fluctuations inside the encapsulated PCM in the building structure.

2. MATERIALS AND METHODS

2.1 PCM 3D-printing layer

SP31, an inorganic hydrated salt, was employed as the PCM in this investigation. The study prefers this kind of PCM because it is non-toxic, has a high thermal storage capacity, and has a melting point that is within the temperature range necessary for the application under consideration. Table 1 shows the thermophysical characteristics of the PCM.

The design process of creating a 3-dimensional item from CAD software or a digital 3D model is known as 3D printing. The new PCM 3D-printing layer designed by this method has a thickness of 2 cm and a width of 45 cm x 45 cm. The device available cannot make a layer of 45 cm x 45 cm, so it is made with nine pieces of 15 cm x 15 cm, working on a large area gives more accurate experimental answers and also brings it closer to practical achievements. The proposed layers of samples have dimensions of 45 cm x 45 cm. The model is drawn in the Auto Cad program and transformed into a 3D printing machine. Figure 1 depicts a sample that has dimensions of 2 cm thick, 15 cm high, and 15 cm wide, also two gaps in the sample, each measuring 14.6 cm in height and 6.9 cm in breadth. The gap is 1.2 cm in thickness. The thickness of the walls next to it and below is 4 mm.

Table 1. Properties of SP31 PCM (inorganic)

Thermal conductivity (W/m. K)	0.5
Melting point temperature (°C)	32
Heat of fusion (kJ/kg)	210
Specific heat capacity (kJ/kg. K)	2
Density solid (kg/l)	1.35
Density liquid (kg/l)	1.3

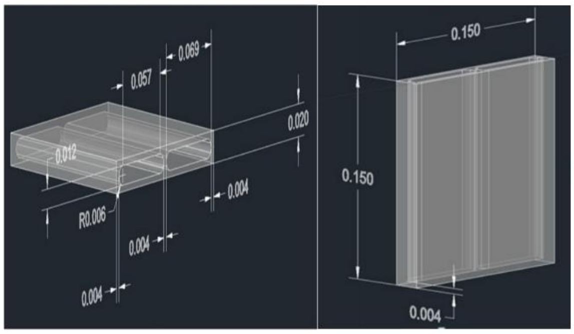

Figure 1. Sample PCM 3D-printing created by Auto CAD program

As shown in Figure 2, the printed samples use the Auto cad program and the 3D printing machine of UP BOX+. The UP BOX+ is a three-dimensional printing machine, accurate and not complex. The UP BOX is compatible with a wide range of filaments and comes with simple software. The polylactic acid (PLA) material is used to print out the samples because it is cheap and abandoned. The material, PLA, has a thermal conductivity of 0.13 W/m.K. The PCM is heated to the top of the melting point until it melts completely. It will be liquid, and then it will be put into the gaps in the samples, the volume of each gab is 0.12 liter. as shown in Figure 3.

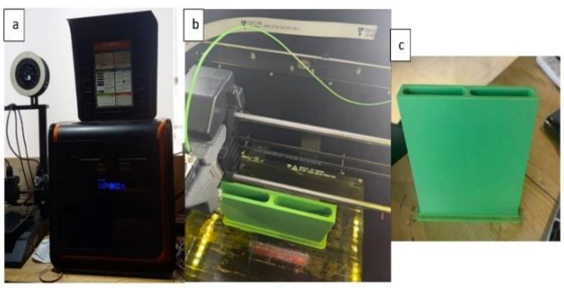

Figure 2. UP BOX+ device **a**. outlet device, **b**. space of printing device, **c**. sample PCM 3D-printing

Figure 3. Setup PCM material in the gab sample

2.2 Small pilot house

As shown in Figure 4, a small house, MDF type, was used as a pilot to trial the thermal performance of walls with phase change material. Both sizes of rooms are 100 cm x 45 cm x 45 cm. The layer separates two rooms, the first one the gypsum board alone, and the second one uses PCM with and without the gypsum board. The second room assumes that the constant temperature is equal to 19.25℃. To control the temperature of the first room, the heating system, light bulbs 100 Watts, were used for the variation of temperatures between 19.25℃ and 55℃ the step size of the first room temperature was one minute during six. These heat sources were connected to a datalogger and variable resistance that was set up for room one with a basic accuracy of 0.1 percent, the heat load on inlet wall surfaces that could be seen in typical outside conditions. The first room in this layout simulates the practical outside temperature. The second room represents the temperature of the interior conditions of the space of the building. The temperature of the pilot's various locations was measured for nine hours in different pilot structures. However, the heat sources were only turned "on" for six hours to measure the solar load on the walls during the same time. Then the heat sources were turned "off," and the walls were allowed to cool for three hours before being switched back on. The round was repeated many times. The thermal properties of the inlet surface walls of the pilot house acquired throughout the trials were designed to be as comparable as feasible to the temperature distributions of the external surface walls of the building. There were two ways to do this: control the data logger and change the resistance of the heat sources that were making the heat.

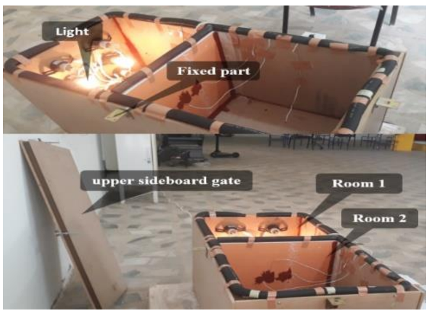

Figure 4. Sketch of small pilot house

The pilot house's usual weather conditions were patterned after summer weather conditions in Erbil, Iraq. Under these conditions, the thermal loads caused by the wall heat sources were about the same as those on building surfaces that are exposed to the outside of the wall.

2.3 Measurement devices

Commercial thermocouples are reasonably priced, interchangeable, have standard connections, and can measure a wide range of temperatures. In contrast to most other temperature monitoring approaches, thermocouples are self-powered and do not require any external stimulation. Precision is the primary limitation of thermocouples; system errors of less than one degree Celsius (°C) may be difficult to achieve. The length and diameter of the wire are 1 m and 4 mm, with a temperature range of (-40°C to 400°C).

The Thermocouple K type has 10 wires in the rooms, surface layers, and between the layers used in this work. The Thermocouples were calibrated before usage to make sure their reading was correct, with limits of error of 0.02℃.

3. EXPERIMENTAL PROCEDURE

In this work, 3D printing methods were used to design and produce a specified PCM shape. The model was then tested. The fact is that it is lightweight and has good structural strength. The experimental procedure was first to insert only the gypsum board layer, monitoring the temperature of the inlet wall surface, outlet wall surface, and room two during the test. Second, they added PCM 3D printing to the gypsum board layer in front of the heat source, monitoring the temperature of the outer wall surface, inner wall surface, and room two during the test and comparing this.

4. RESULTS AND DISCUSSION

Figure 5 indicates the difference in temperature of the outer wall surface (this wall is the opposite of the heat source for room one) during the experiment. It illustrates the melting point during the test from up to down in the gap of the PCM 3D-printing layer. It's understandable that the temperature of the wall, like the heat source temperature, rises with time. However, the wall with PCM exhibited a relatively slow increase compared to the wall without PCM. The quick increase in temperature of the wall is lessened by the entrance of some of the heat energy toward the encapsulated PCM in the PCM 3D-printing layer in comparison to the case of the wall without PCM. The PCM absorbs the heat energy, which defends the outer wall from hotness. The investigation revealed that the test recorded peak wall temperatures of 51℃ and 46℃, respectively, with walls without PCM and walls added with a PCM 3D-printing layer. In other words, the results show that by 3D-printing PCM on a surface, the temperature of the peak outer wall temperature dropped by 5℃.

Figure 6 illustrates the surface wall temperature inside room two during the test. Due to heat conduction, the temperature of the surface wall increased proportionately with the temperature of the outer wall surface. However, adding a layer of PCM 3D printing to the wall reduces the surface wall's temperature during the test. PCM absorbs more heat than other materials, preventing heat from entering the wall. The inner surface temperature of the wall without PCM was 42℃, while it was 32.5℃ for the PCM 3D-printing layer. With the aid of the PCM 3D-printing layer, it is evident that the test temperature of the inner wall was reduced by 9.5℃.

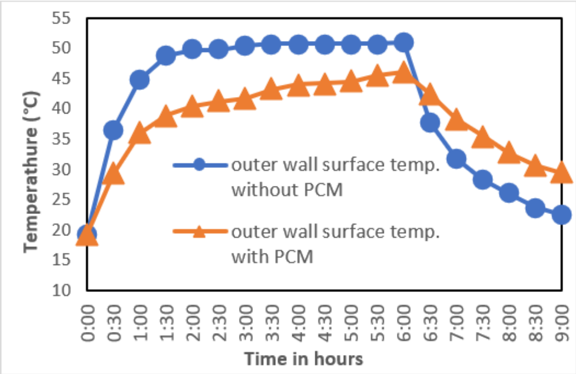

Figure 5. Outer wall surface temperature with and without PCM

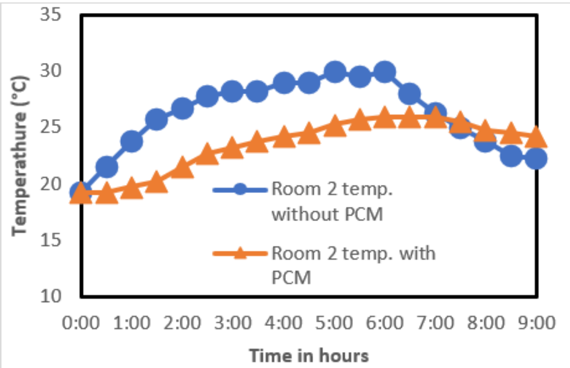

Figure 6. Inner wall surface temperature with and without PCM

Figure 7 depicts the interior room temperature during the test for the case where the wall without PCM and the PCM 3D-printing layer wall construction. When there was no PCM, the inside temperature soon increased. The addition of the PCM 3D-printing wall layer, on the other hand, resulted in a very small variation in room temperature throughout the test. Without PCM, the wall temperature rose to 35°C, but adding a PCM 3D-printing layer prevented the indoor temperature (room two) from rising above 30°C. The PCM 3D-printing layer reduced the peak room temperature by 5°C.

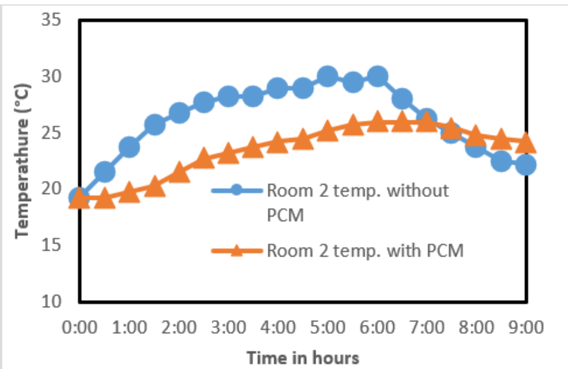

Figure 7. Indoor room two temperature with and without PCM

5. CONCLUSIONS

In this study, PCM 3D-printing was created and manufactured using 3D printing technologies. The materials have a lightweight nature, structural strength, and low cost. The Polylactic acid substance used to print the layer because of its sensitivity to high temperatures, particularly its low heat deflection temperature, and its susceptibility to deterioration over time. The results of the investigational prosecutions are as follows.

The outer wall surface temperature was diminished by 5°C at the peak load by using the PCM 3D-printing layer.

The use of PCM resulted in a 9.5°C decrease in wall surface temperature during peak load hours.

The overall temperature reduction of the interior room was 4°C throughout the peak load hour with the presence of the new model.

As a result, it is proposed that additional research be conducted into the PCM layer of the building walls to reduce the temperature inside the buildings and improve thermal management.

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