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Investigation of Thermal Performance of Integrated Phase Change Materials in Building Structure

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ABSTRACT

About 40% of the world's primary energy is used by buildings. This indicates that the bulk of greenhouse gas emissions are caused by buildings. In this investigation, the decrement factor (DF) and time lag (TL) of a new 3D-printed model are experimentally determined. It is really time to cut back on such energy consumption to lessen buildings' negative environmental effects. The introduction of new model 3D-printing blocks with high thermal inertia might be a way to lower the building's energy usage. Decrement factors and time lag are characteristics of thermal inertia. In this investigation, the decrement factor and time lag of a new 3D-printed model are experimentally determined. At the University of Salahadin's College of Engineering, a pilot house measuring 1 m x 0.45 m x 0.45 m is constructed specifically for this application. The equivalent temperatures of the inside (room one) and outside (room two) are used to determine the decrement factor and time lag. The findings indicate that using the new 3D-block model, the time lag is around 120 minutes, and the decrement factor is approximately 0.34. The 3D-printing block enables a 4.5°C reduction in the peak interior temperature. Since temperature changes outside are not noticeable, less energy is used to cool the structure during warm weather.

Keywords:

Decrement factor, Time lag, 3D-printing block, Thermal inertia, Phase change material.

1 INTRODUCTION

The high energy consumption in cities accounts for more than 70% of greenhouse gas emissions [1]. By 2035, buildings will rank as the 4th source of greenhouse gas emissions due to their high energy consumption [2]. The primary goals of research on sustainable buildings are to develop novel techniques for storing renewable energy and to expand our understanding of passive heating and cooling systems. Phase change materials (PCM) are currently needed in construction materials if buildings are to retain efficient energy performance [3]. This material's main benefit is its capacity to store more energy in a given volume at a greater temperature because of latent heat rather than sensible heat. PCMs are used to change the peak load into an off-peak load, improving the building's efficiency.

According to several studies, adding thermal mass to building structures can reduce heating and cooling costs in residential buildings by 5 to 30 %[4]. In 1948, the first study of using PCM in structures was carried out [5]-[6]. A section of the solar heating system in a 135 m^2 house employs metal cans loaded with Glauber's salt. It also contained a solar heating system that employed 4 m^3 metal containers packed with Glauber salt and was incorporated into the sunspace house's well-ventilated glass façade. The experiment was successful in heating the room for two and one-half seasons during the winter and cooling it during the summer using heat produced by the passive solar system.

Sharma et al. [7] assert that enhanced building envelopes by using PCM technology have the potential to significantly decrease the cooling energy needs of residential structures in Delhi (the capital of India). Their study examined the effect of critical PCM design aspects such as material thickness, placement, and melting point temperature on predicted energy savings, and compared the findings to those achieved with insulation-enhanced envelopes. Summer heat gain was decreased by 12.6-36.2% with a PCM coating on the roof but was reduced by 46.0-71.4% with an insulating layer of the same thickness. Additionally, heat gain via PCM-enhanced walls was reduced by 10.4-26.6%, but heat gain through insulated walls was reduced by 34.7-64.0%. PCMinsulation-enhanced envelopes have the potential to decrease Delhi's yearly energy consumption and greenhouse gas emissions by 0.3-1.5% and 0.2-1.0%, respectively, compared to current levels of energy and CO_2.

Two factors that describe a material's thermal inertia are time lag and decrement factor. Time lag (TL) and decrement factor (DF) have been the subject of much research. A wall with a thermal capacity (1.512 MJ/m3 K) and a thermal conductivity (0.62 W/mK) has been evaluated for TL and DF by Jin et al. [8]. Thongtha et al. [9] calculated the TL and DF of two types of autoclaved cellular concrete walls: one without sugar sediment addition, and one with it. Ruivo et al. [10] calculated the TL and DF of different walls with dark or light colored outside surfaces. The aerated autoclaved concrete wall's TL and DF have been calculated by Assem [11]. The TL and DF of buildings with laterite walls have been investigated by Shaik et al. [12]. Fathipour et al. [13] have looked at the TL and DF of several building materials that are often used in Iran. The TL and DF of insulation construction materials for walls have been assessed by Al-Sanea et al. [14].

There are several potential applications for the additive manufacturing technique, also known as 3D printing, in the fields of electrical, biological, metal and alloy, automotive, aerospace, and architecture [15]-[16]. Researchers have studied the use of 3D printing for energy conversion and thermal insulation. Jafari et al. [17]claim that the recommended 3D-printed wick would improve heat transfer efficiency due to its capillary performance and excellent permeability. When Salih et al. [18]used a PCM 3D printing layer to create a new model layer in walls, the temperature peak indoors was decreased by 4.5°C. The 3D printed lattice structure satisfies requirements for space applications in terms of heat transfer, weight, optical, mechanical, acoustic, and other factors. Unknown characteristics like heat storage rate and equivalent thermal conductivity will be introduced.

These theoretical and experimental experiments are all focused on calculating the wall's decrement factor and time lag. In these investigations, the walls are subjected to circumstances that differ from those found in tropical climes. Using a novel 3D-block model, this work aims to empirically establish the time lag and decrement factor. A pilot house has been constructed at Salahadin University in Erbil, Iraq in an effort to achieve this. When compared to the study stated above, this work is unique in that it calculates TL and DF by using the inside temperature (room one) and outside temperature (room two). Room one represents the temperature of the air outside, and room two represents the temperature of the air inside.

2 MATERIAL AND METHOD

2.1. Model setups

A small pilothouse was built from an MDF board with interior dimensions of 1 m x 0.45 m x 0.45 m. The interior part of the module was separated by a PCM layer and gypsum board. The temperature in the second room is assumed to be constant. However, the temperature in the first room is controlled by using two 100-watt lights, and they are used as a heat source to generate a different temperature in the room. As shown in Figure 1, room one of the pilot-house represented the exterior of a building, while room two of the pilot house represented the interior conditioned region of the building.

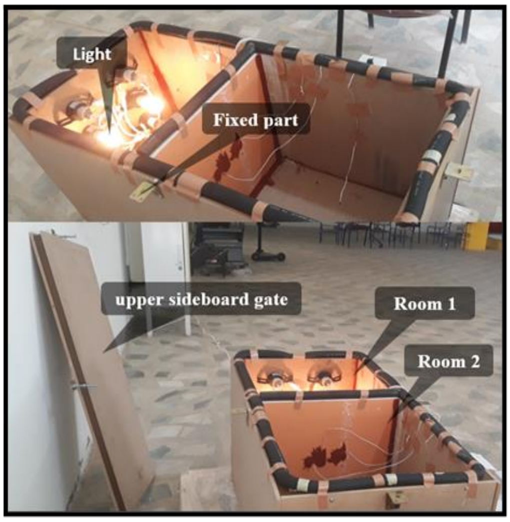

Fig.1 Sketch of small pilot house

2.2. 3D-printing block

3D printing is the technique of creating a three-dimensional object from a CAD model or a digital 3D model. A 3D printing device creates a new model of the 3D-printing block. It is constructed of nine 0.15 m × 0.15 m pieces and has a 0.02 m thickness and 0.45 m x 0.45 m breadth since the existing technology cannot produce a layer of that size. The samples were arranged in three rows and columns to create a 0.45 m x 0.45 m new model block. The three-dimensional shapes of the 3D printing examples were designed with the Auto CAD software for this research. The thickness is 0.02 m, the height is 0.15 m, and the width is 0.15 m. Two gaps in the sample have a height of 0.146 m and a width of 0.069 m. The gap measures 0.012 m in thickness. The walls below and next to it are 0.004 m thick. The sample created with the Auto CAD program was printed with a UP BOX+ device. The UP BOX+ is a 3-D printing device that is used to print three-dimensional shapes at the same time. Nine samples were printed. The figure was printed by using the material Polylactic acid (PLA). Polylactic acid has a thermal conductivity of 0.13 W/mK as shown in Figure 2.

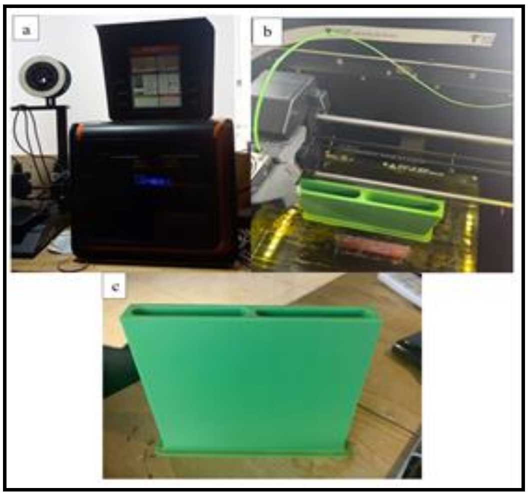

Fig.2 UP BOX+ machine a. outlet device, b. space of printing device, c. sample PCM 3D-printing

2.3. PCM material properties

Paraffin wax, also known as RT28HC, was employed in this study as a latent heat material because it has a large thermal storage capacity required for the application under consideration. The liquid state temperature of paraffin is 27°C, and the solid-state temperature is 29°C. The material has 180 kJ/kg of latent heat. The thermal conductivity for paraffin wax is 0.2 W/m.K. Paraffin wax, 0.24 litres per sample, was present.

2.4. Experimental setup

The gypsum board, 3D-printing PCM layer, and one type of Phase Change Materials were tested. The testing progressed to a steady state. Setup materials (phase change materials) are heated to the melting point until they completely melt (they will be a liquid) and then placed in the encapsulated model as shown in Figure 3. The data logger used to record temperatures over time contains Variable resistors that can adjust the resistance from zero to a predetermined maximum value control. These heat sources were wired into a variable resistance and a datalogger that was configured for room one and had a basic accuracy of 0.1 percent. The variable resistance is prepared to control the light in room one until the temperature is increased from 19.5°C to 55°C for six hours, and then the light is turned off for a

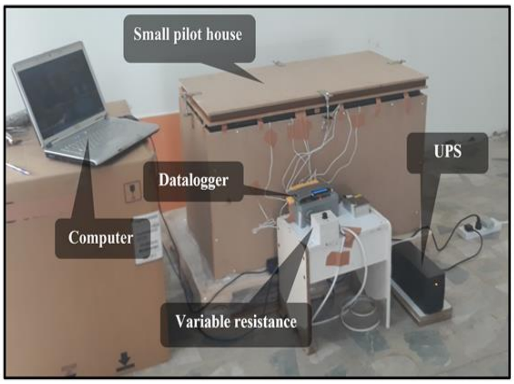

Fig.3 Procedure of thermal performance test

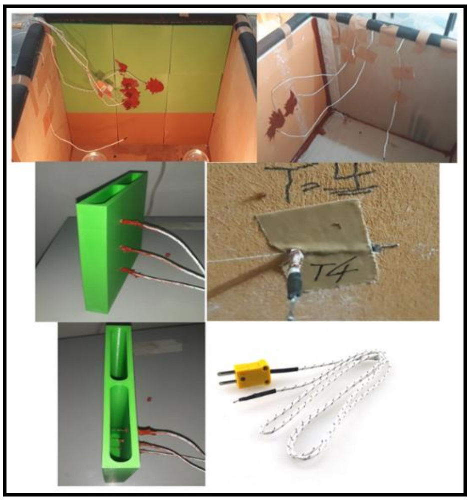

Fig.4 Sketch and place of the thermocouple

decreased temperature for three hours.

Temperature measurements are made by using ten k-type thermocouples. Thermocouples were calibrated before use as shown Table 1. The device is set up so that throughout the course of nine hours, temperature readings are consistently and frequently taken in room one, room two, the phase-change material layer, and on the inner and outer surfaces. Figure 4 displays the model's schematic diagram as well as the distribution of thermocouples. In this study, a specific PCM form was designed and created by using 3D printing techniques. Then the model was examined. Its small weight and strong structural design are facts. The only layer of gypsum board was initially inserted as part of the experiment, and the temperatures of room two, the outlet wall, and the intake wall were all kept track of. In addition, a 3D printing block on the layer of gypsum board in front of the heat source was used. The temperatures in room two, the inner wall, and the outer wall were monitored and compared while running the test.

Table 1: Accuracy of the temperature apparatus and error

Device	Accuracy%	Error Rate%
TemperatureSensitive	99.284	±0.716

3. Decrement factor (DF) and Time lag (TL)

The thermal performance of a PCM-enhanced wall was investigated by using two common metrics: Decrement Factor (DF) and Time Lag (TL) [19]. The two parameters time lag and decrement factor are calculated, the first from the time lag for the heatwave to travel from the outside air to the interior wall surface, and the second from the ratio of reduction in the heatwave amplitude during this propagation as shown in Figure 5.

Their thermal mass capacity is used to describe a wall's or roof's thermal mass capacity and can be calculated in the following ways:

$$TL = t\left(T_{sur\_inner,max}\right) - t\left(T_{sur\_outer,max}\right) \quad (1)$$

$$DF = \frac{Amp_{inner}}{Amp_{outer}} = \frac{T_{sur\_inner\_max} - T_{sur\_inner\_min}}{T_{sur\_outer\_max} - T_{sur\_outer\_min}} \quad (2)$$

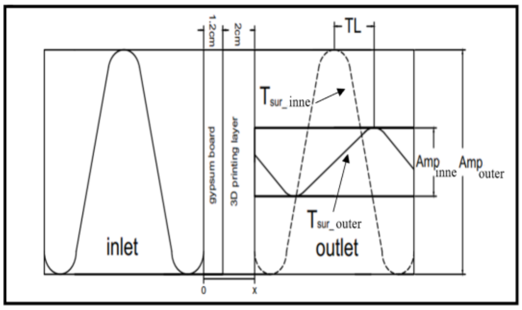

Fig. 5 Decrement Factor (DF) and The Time Lag (TL) are shown schematically on the wall

4. RESULTS AND DISCUSSIONS

4.1. Effect of temperature and place on the wall surface and room

Figure 6 represents the temperature difference between its exterior wall surface (the wall facing room two) during the experiment for RT28HC material with and without PCM. It depicts the melting point as it moves from the top to the bottom of the incapsulated area for the 3D-printing block during the test. When compared to the non-PCM-treated wall, the PCM-treated wall shows only a minor temperature increase. In contrast to a non-PCM wall, the rapid increase in temperature of the 3D-printing block was moderated by the entry of a portion of heat energy into the encapsulated PCM. The phase change material absorbs heat energy, which helps keep the exterior wall from being too hot. Peak wall temperatures fell from 51°C to 48°C for walls without and with a 3D-printing block, respectively. As a result, according to the data, the PCM dropped the peak exterior wall temperature by 3°C.

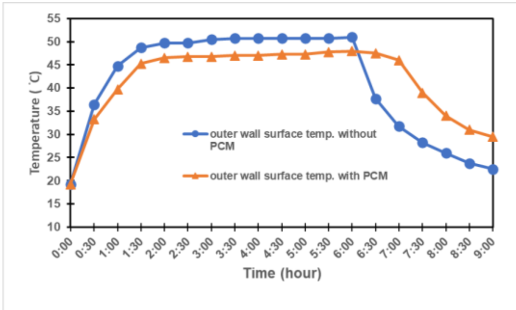

Fig.6 Surface temperature of the outer wall with and without PCM

As shown in Figure 7, the wall surface temperature inside room two was roughly constant throughout the experiment. According to the investigation's findings, heat conduction caused the surface wall temperature to rise in proportion to the outer wall surface temperature. In addition to that, adding an extra layer of 3D-printing to the wall explains the reason for the reduction in the wall surface temperature throughout the test. This is because PCM absorbed a greater proportion of the heat, preventing heat from passing through the wall as it did in the previous test. The interior wall surface temperature without PCM was 42°C, but the surface wall temperature with the PCM 3D-printing layer was 29.25°C. Using the 3D-printing block resulted in a 12.75°C reduction in the inner wall test temperature.

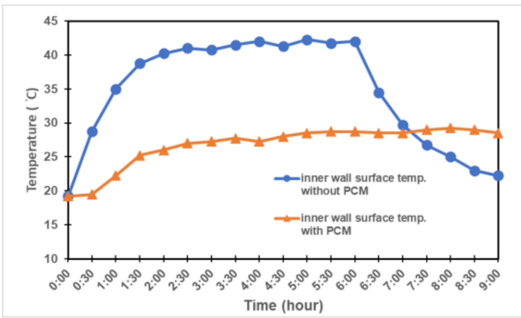

Fig. 7 Surface temperature of the inner walls with and without PCM

Figure 8 displays the indoor room temperature oriented towards the cases of the wall without phase change material and the 3D-printing block wall developed during the test. It is readily seen that the temperature indoors swiftly skewed up when no phase transition material is found. But, it is noticed, that the 3D-printing wall block exhibited a very tiny shift in ambient temperature during the test. The temperature increased to 30°C for the wall without phase change material, although adding the 3D-printing block didn't elevate the inside temperature (room two) over 25.5°C. The PCM 3D-printing block dropped the peak room temperature by 4.5°C.

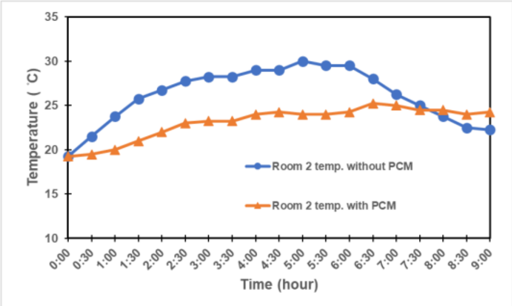

Fig. 8 With and without PCM, the temperature of indoor room two

4.2. Effect of Decrement factor and Time lag

The thermal performance evaluation of walls combined with phase change material is given and discussed. The numerical model creates the temperature development across the wall layers. Only the outer and inner surface temperatures are employed to compute the daily time lag and decrement factor parameters. The test is done for nine hours. To evaluate the thermal performance of the walls, an average value of time lag and decrement factor is calculated.

When compared to the peak phase change temperatures of the phase change material, a parametric is used to characterize the thermal performance of the phase change material integrated wall. Indeed, the efficiency of phase change material is strongly connected to its activation frequency[20]. Thus, an appropriate selection of the peak temperature should avoid the phase change material from staying continuously in the same condition (i.e., liquid or solid-state).

The time lag and decrement factor values for various wall orientations at peak temperature are shown in Table 2. In general, a wall with a low decrement factor and a high time lag improves thermal performance during the hot season [21]. Indeed, as the decrement factor decreases, the amplitude of the Tsur-inner variation decreases, potentially reducing cooling/heating loads during the day [22]. On the other hand, a longer time lag period suggests that the Tsur-inner reaches its peak value later after being able to use the nighttime outside air for natural cooling.

Table 2: Decrement Factor and Time Lag

Gypsum board without PCM		RT28HC with PCM	
TL (min)	DF	TL(min)	DF
20	0.72	120	0.34

Returning to Table, it can be seen that the best results were obtained with the PCM-RT28HC. The DF value is 0.34, and the TL period is 120 minutes.

5. CONCLUSIONS

The tests of the research were conducted in two scenarios: one without PCM and one with a new model of 3D-printing block added inside the wall. RT28HC, an organic, was used as PCMs for the encapsulated samples. In a small pilothouse, the real-time experiments lasted nine hours. The investigational prosecution's findings are summarized below.

- The outer wall surface temperature decreased by 3oC at peak load when the PCM 3D-printing block was used.
- When the RT28HC material was employed, the inner wall surface wall temperature was reduced by 12.75 oC by using the 3D-printing block.
- The temperature in the indoor room was reduced by 4.5°C during the peak load time due to the presence of the new model, due to the use of RT28HC material.
- Thermal performance is evaluated by using the time lag and decrement factor parameters. The influence of the PCM phase change point on various wall faces has been investigated and discussed. By lowering the DF and extending the TL time, an appropriate phase-change temperature enhances the thermal performance of the 3D-printing block. The RT28HC PCM provides excellent thermal performance. It produces the greatest results DF = 0.34 and TL = 120 min).

In order to lower indoor temperatures and enhance thermal management, it is suggested that more studies might be done on the 3D-printing block of building walls.

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Nomenclature

Symbol	Description
Amp_{inner}	Amplitude inner
Amp_{outer}	Amplitude outer
DF	Dectement factor
TL	Time lag (minute)
$t(T_{sur\_inner,max})$	time of maximum inner surface temperature (minute)
$t(T_{sur\_outer,max})$	time of maximum outer surface temperature (minute)
$T_{sur\ inner\ max}$	maximum inner surface temperature°C
$T_{sur\ inner\ min}$	minimum inner surface temperature°C
$T_{sur\ outer\ max}$	maximum outer surface temperature°C
$T_{sur\ outer\ min}$	minimum outer surface temperature°C

دراسة الأداء الحراري لمواد متغيرة الطور المتكاملة في هيكل المبنى

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الملخص

تستخدم المباني حوالي 40٪ من الطاقة الأولية في العالم. يشير هذا إلى أن المباني تسبب الجزء الأكبر من انبعاثات غازات الاحتباس الحراري. في هذا التحقيق ، تم تحديد عامل التناقص (DF) والتأخر الزمني (TL) لنموذج جديد مطبوع ثلاثي الأبعاد بشكل تجريبي. لقد حان الوقت حقًا لتقليص استهلاك الطاقة هذا لتقليل الآثار البيئية الضارة للمباني. قد يكون إدخال كتل الطباعة ثلاثية الأبعاد النموذجية الجديدة ذات القصور الذاتي الحراري طريقة لتقليل استخدام الطاقة في المبنى. تعتبر عوامل التناقص والتأخر الزمني من خصائص القصور الذاتي الحراري. في هذا التحقيق ، تم تحديد عامل التناقص والتأخر الزمني لنموذج جديد مطبوع ثلاثي الأبعاد بشكل تجريبي. في كلية الهندسة بجامعة صلاح الدين ، تم بناء منزل تجريبي بقياس 1 م × 0.45 م × 0.45 م خصيصًا لهذا التطبيق. تُستخدم درجات الحرارة المكافئة للداخل (الغرفة الأولى) وخارجها (الغرفة الثانية) لتحديد عامل الإنقاص والفاصل الزمني. تشير النتائج إلى أنه باستخدام نموذج الكتلة ثلاثية الأبعاد الجديد ، فإن الفاصل الزمني يبلغ حوالي 120 دقيقة ، وعامل الإنقاص حوالي 0.34. مكّن قالب الطباعة ثلاثية الأبعاد من تقليل درجة الحرارة الداخلية القصوى بمقدار 4.5 درجة مئوية. نظرًا لأن التغيرات في درجة الحرارة بالخارج غير ملحوظة ، يتم استخدام طاقة أقل لتبريد الهيكل أثناء الطقس الدافئ.

الكلمات الداله :

عامل التناقص الوقت الضائع؛ كتلة الطباعة ثلاثية الأبعاد ؛ القصور الذاتي الحراري؛ مواد تغيير المرحلة.