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An experimental study of the thermal behavior of bricks integrated with PCM-capsules in building walls

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ABSTRACT

Buildings are the major energy users and by 2035, they will be the fourth largest source of greenhouse gas emissions. Phase change materials (PCMs) are applied to shift the peak-load to the off-peak-load, positively effecting the efficiency of the building. In this paper, an experimental embedding of PCM (Paraffin) with bricks in conventional wall layers is carried out. The effect of this on the thermal diffusion of the inner surface of the wall is studied. Capsules are manufactured to fit the size of the holes inside the bricks and they are filled with Paraffin (147 kJ/kg latent heat, 38°C solidified and 43°C liquidised) and closed in a way that prevents leakage. Each brick contained two rows of holes (5 holes per row). Capsules are placed in the holes at a rate of 5 capsules per brick and 10 capsules per brick. Three wall samples are experimentally tested: traditional wall, wall containing 5 capsules/brick and a wall containing 10 capsules/brick. The indoor test with light intensity has been fixed on 900 W/m² during the heating period for 4 hours and the remaining period of cooling. The temperature measured and recorded for the internal, external surfaces and the middle of the wall using K-type thermocouples and datalogger. The results indicated that, bricks wall with 10 PCM- capsules per brick reduced the heat flux by 34.17% compared with traditional wall sample, and energy stored 50% more than a wall with 5PCM-capsules per brick. The lowest temperature of the internal wall surface of sample 10 capsules per brick is recorded compared to the reference wall where the difference is more than 3°C.

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1. Introduction

By 2035, buildings will be the leading consumers of energy and a significant source of greenhouse gas emissions [1, 2]. Developing new techniques to store renewable energy and further exploring heating strategies and passive cooling is one primary subject in sustainable building research. Phase change materials or PCMs are applied to shift the peak-load to the off-peak-load, positively effecting the efficiency of the building. Various studies have shown that integrating thermal mass in building structures may save 5% to 30% on cooling and heating energy in

residential buildings [1, 3]. Phase change materials can be classified into three categories: organic PCM, inorganic PCM, and metal and metal alloy PCM Fleischer [4]. Paraffin and fatty acid are types of organic PCM. The phase change range of the paraffin is often between 35 °C and 70 °C, convenient to the electronic application that often has a maximum junction temperature of 85 °C. while, fatty acids are more suitable for residential application because it has lower melting points paraffin. In addition, a fatty acid is commonly studied PCMs for reducing HVAC costs [4]. The main elements in the formation of the inorganic PCMs types are salt and

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Nomenclature		Greek symbols	
C _p	Specific heat (J/ kg. K)	ρ	Density (kg/m ³)
PCM	Phase change material	Λ	Latent heat of fusion (kJ/kg)
k	thermal conductivity (W/ m.K)	ϕ	Porosity
E	Energy (kJ)	Subscripts	
T	Temperature (°C)	RW	Reference wall (traditional wall)
m	Mass (kg)	Se	External surface
Q	Heat flux (W)	Si	Internal surface
ΔT	Temperature difference (°C)	b	brick

salt hydrates. The nature of phase changing material mechanism in which the material melt and freeze at operation time makes integrating phase-changing material into construction components a significant difficulty. As a result, whether PCM packages are built-in micro or macro encapsulation is determined by the integration needs [5-7]. Tiago Silva *et al.* [8] studied the integrating PCM with building materials by experimental tests and numerical simulation. The study tested the impact of adding PCM to a standard Portuguese brick in an experiment. They constructed a macro capsule made of steel and filled it with PCM, and then he added the capsule to the hollows in the brick at adequate dimensions. Concrete mortar was used as an added ingredient to build the wall. The PCM used was paraffin RT18 with melting temperature of 18°C. The numerical results were compared the experimental tests results in order to validated it. They achieved a reduction in temperature from 10 to 5°C, plus diminishing the fluctuation in the indoor space temperature, and achieved a three hours’ time-delay. Xing Jin *et al.* [9] examined the PCM’s thermal performance and predicted where it should be placed in the system. The "PCM thermal shield (PCMTSs)" configuration of encapsulating PCM was utilized in this research. PCMTS involves sandwiching PCM between two layers of covering aluminum foil after encapsulating the PCM in fat polyethylene bubbles. The size of the aluminum foil was (60.2 cm x 40.6 cm). At various distances from the inner surface of the wallboard, the thermal heat behavior of the walls with phase change materials was observed. The boundary layer was the furthest away from the heating source in the simulator. Using a high transient wall modeling program, the optimum position for the PCM layer, according to the findings, is 1/5 L of the exposed inner surface furthest from the heat source. The maximal heat flow attenuation at this site was 41%, with 2 hours for load shifting. It is worth mentioning that the PCM that was used in this experiment was a proprietary hydrated salt. With a phase transition temperature range of 24°C-34°C, the latent heat was 140 kJ/kg. Osama, *et al.* [10] built two walls, one wall had been treated with paraffin wax, and the other was a traditional Iraqi wall. The treated wall thickness dimension was of 0.5 cm external layer of concrete, followed by a 2cm layer of (80% cement mixed with 20% Paraffin wax). The next layer was 24cm of typical brick and 2cm of gypsum as internal layer. The second traditional wall had an external layer of 2.5cm thickness of concrete, followed by a 24cm layer of brick and the internal layer is 2 cm of gypsum. The two walls models had contained eleven thermocouples K-type, which were implanted through their centerline from the external surface to the internal surface. The paraffin capsules had been wrapped in

aluminum foil with a thickness of (0.06mm), and then it was covered by an adhesive coating to prevent any leakages. A capsule dimension was 0.8cm x 0.8cm. The two wall models had a dimension of (300mm x 300mm) and had been insulated from four sides by a glass wool layer, so the energy exchange was kept in one direction, and the heat loss was reduced. The researcher had achieved a difference of (1.6°C) between the treated and non-treated walls. The heat flow toward the interior surface was reduced when the wall was coated with phase change material because of its heat storage ability. The focal point of this paper is integrating macro capsules filled with paraffin into the bricks of the traditional wall, and study the thermal behavior of PCM under constant radiation.

2. Description of the experimental system

2.1. Phase change material

Thermodynamically the phase is defined as the homogeneous state of the materials, which is the chemical arrangement and physical state of matter. The phase of a substance changes (solidify or melt) at a specific temperature and pressure [11]. Phase Change Material (PCM) is the material that undergoes a phase transformation, where PCMs may absorb and release heat during phase transitions (mostly from the solid to the liquid state and vice versa) at a reasonably constant temperature as shown in Fig. 1 [12]. Phase change materials (or latent heat materials) have the ability to store and release large quantities of heat [4, 11]. Paraffin wax which refers to as RT-42 was used in this study as a latent heat material.

Table 1. Thermos-physical properties of building materials used [12].

	K(W/m.K)	C(J/kg.K)	ρ(kg/m ³)
concrete	0.99	2040	2020
brick	0.66	1060	1880
paraffin	0.2	2000	899 (solid) 760 (liquid)

The Liquid temperature of the paraffin is 43°C, and the temperature at which the material solidifies is 38°C. The latent heat of the material is 147 kJ/kg. Paraffin wax has a thermal conductivity equals to 0.2 W/m.K [6]. The term (λ)referring to latent heat of fusion, which is variable for each material, is used in equation (1) to determine the energy storage potential in a given quantity of mass m.[4].

$$E_{stored} = m\lambda \text{ (kJ)}$$

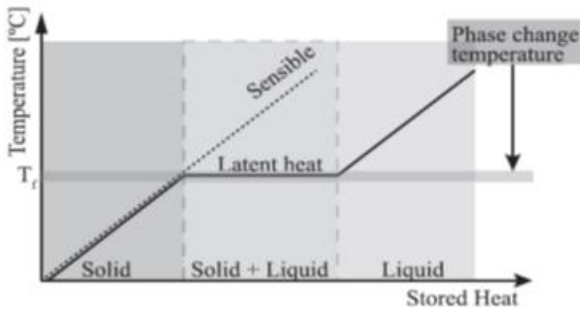


Figure 1. The phase change material.

(1)

2.2. Experiment set up

The experiments took place at Al-Qadisiyah University, college of engineering. A small room was built as shown in Fig. 2. The room was built using a cube-shaped iron frame with dimensions of (110 x 110 x 100 cm) and was insulated using a sandwiched panel with 5 cm thickness. On one side of the room, a 60x60 cm void was left for a wooden frame with 5 cm thickness to be fitted. A total of three samples was built in this experiment. Each wall was built at a time inside the wooden frame for the experiment to be conducted separately on each sample. The walls of the experiments had a dimension of (50 x 50 x 28cm). The first wall sample was traditional wall made of 2 cm layer of concrete followed by 24 cm layer of perforated brick followed by 2 cm layer of concrete. In order to make a suitable packaging for the paraffin used, a cylindrical capsule was made. For the capsules to fit in the perforated brick holes, the appropriate dimension would be 8 cm high and 2.5 cm diameter. Galvanized iron was used to make the upper, perforated cover and the lower base of the cylinder, and the regular iron to make the body of the cylinder. The iron used was 0.04 cm thick. A needle hole was left at one of the bases of each capsule for paraffin filling through. Each capsule carried 30 g of paraffin wax as shown in Fig. 3. The second wall sample was referred to as C1 and in this sample 50 capsules filled with paraffin was used. The capsules were installed in the first row of the brick’s holes. The third wall sample was referred to as C2 and in this sample 100 capsules were used, and installed in the first and second row of the brick layer as shown in Fig. 4. Four projectors lamps of 1000 watt power were used as a radiation source. The light sources were installed on an iron frame and were situated 50cm away from the wall sample external surface. The radiation intensity used in this experiment was controlled to be a fixed value equal to 900 W/m²

and it radiates vertically on the external surface of the wall. Table 1 shows the building material properties.

The device used to record temperatures overtime was AT45xx with high-performance ARM microprocessor control as shown in Fig. 2. It calculates the temperature data instantaneously during the experiments and stored it into a connected PC. The thermocouple distribution is shown

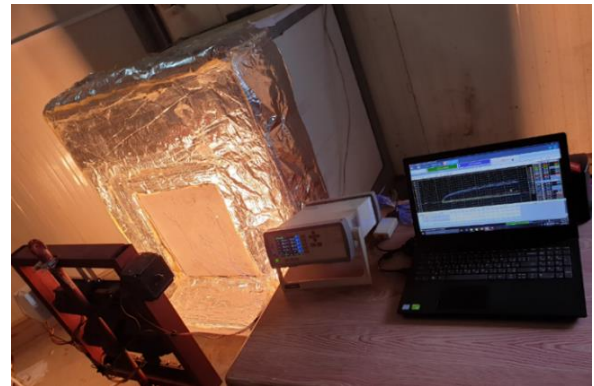


Figure 2. The experimental room with the heat source.



Figure 3. Injecting melting paraffin wax in capsule.

in Fig. 5.

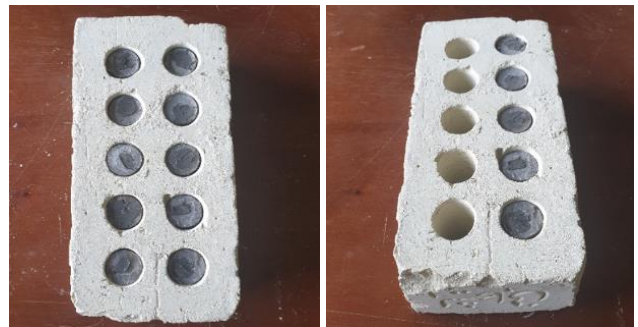


Figure 4. Perforated brick filled with PCM capsule.

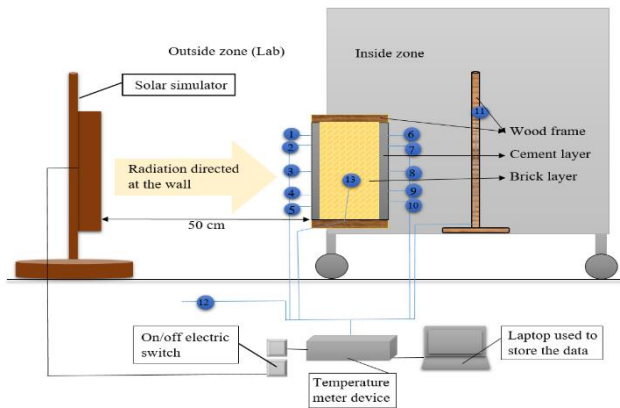


Figure 5. Schematic of the experimental and the distribution of the sensor.

2.3. Theoretical background

Conduction occurs when thermal transmits through the solid media or quiescent fluid. Fourier law demonstrates the heat flow when heat transfer through conduction. The heat moves per unit length in the solid dT/dx [13]. When the wall has more than one material, and each material has different thermal conductivity (k), the temperature gradient happens at each layer [14].

$$Q = -kA \frac{dT}{dx} \quad (W) \quad (2)$$

Moreover, the multilayer wall is called a composite wall, and the heat flow calculation is slightly different. The overall heat transfer term is used when more than one thermal resistance combines conduction and convection exists [14].

$$U = \frac{1}{R} \quad (W/m^2.K) \quad (3)$$

The term (ρ) refers to the density in (Kg/m^3). T_{liquid} ($^{\circ}C$) is the temperature at which the paraffin melt and T_{solid} ($^{\circ}C$) is the temperature at which paraffin solidifies [15]. Here, $\Delta T = T_{liquid} - T_{solid}$, which is equal 5 in case of paraffin wax RT-42 [6].

$$(\rho C)_{PCM} = \left\{ \begin{array}{ll} \frac{(\rho C)_{solid}}{2} & T < T_{solid} \\ \frac{(\rho C)_{solid} + (\rho C)_{liquid}}{2} + \frac{\rho_{solid} + \rho_{liquid}}{2} \left(\frac{\lambda}{\Delta T} \right) & T_{solid} \leq T \leq T_{liquid} \\ (\rho C)_{liquid} & T > T_{liquid} \end{array} \right\} \quad (4)$$

The porous media concept can be applied to the bricks used in the experiment. The experimental wall was made of three layers as shown in **Fig. 6**. Two layers of concrete sandwiched the third layer of perforated bricks. Perforated bricks are porous media of some sort, containing voids

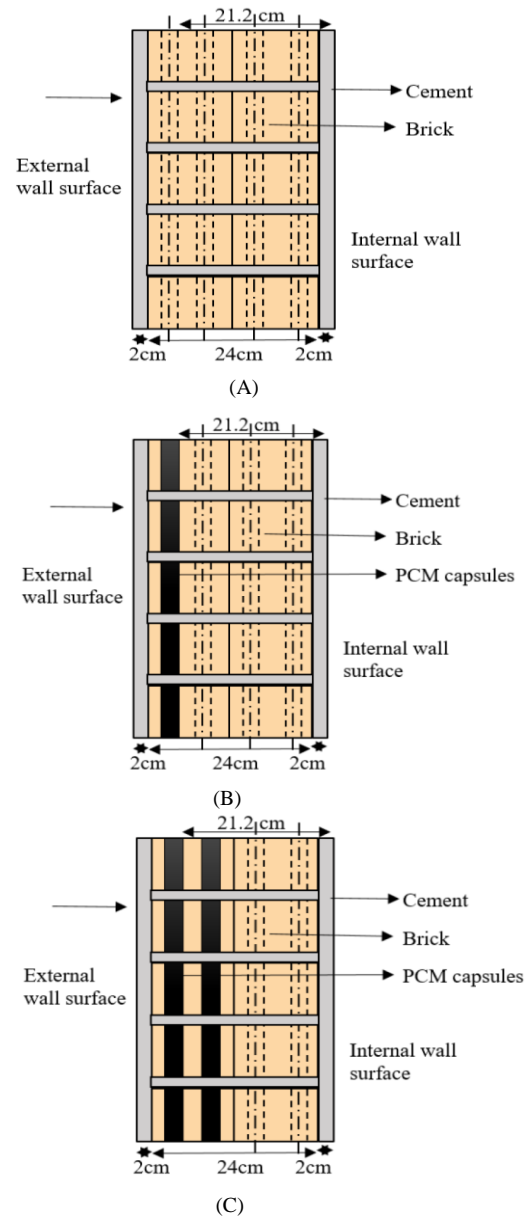


Figure 6. A) traditional wall, B) C1-wall, and C) C2-wall.

of cylinder holes usually filled with air. As will come later, those holes were filled with cylindrical capsules made of iron of small thickness and

filled with paraffin wax. The thermal conductivity of the perforated brick filled with PCM capsule can be calculated from the equation (5) [16]:

$$k_{PCM \text{ capsule}} = (1 - \varphi)k_b + \varphi k_{PCM} \quad (5)$$

For the C1 wall where PCM capsules filled only one row of the brick holes, half the volume of the brick was taken into account during calculation, while in the C2 wall, where all ten holes of the brick were filled with PCM capsules, the whole volume of brick was included. As shown in **Figs. 6(B) and 6(C)**.

When using PCM as part of the wall layers, equation (6) demonstrates the amount of flux that move through the wall. Where Q_{stord} is equal to the heat stored in the phase change material.

$$Q_{cond} = Q_{flux} - Q_{stored} \tag{6}$$

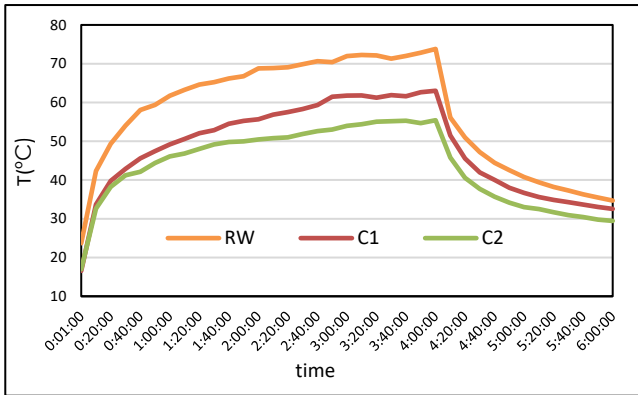


Figure 7. Comparing the external surface temperatures (T_{se}) for walls samples with the reference sample.

3. Results and discussions

Fig. 7 shows the temperature change of the external wall surface with time under the radiation intensity of 900 W/m^2 . After the radiation source is turned on, the temperature of the external surface rises sensibly and significantly in all cases. The temperature of the Traditional wall continues to rise linearly during the first 30 minutes, reaching 54.02°C . The increase continues but less gradually and slows down with the end of the heating period after 4 hours where the temperature reaches its maximum value of 73.8°C . In all the other cases, the same scenario is observed above where the temperature starts to increase sensibly but at a slower rate compared to the case of a Traditional wall. As the heating process continues, the temperature begins to increase at a gradual rate until it reaches its highest values at the end of heating to 63.02°C and 55.42°C at C1 and C2 respectively. The maximum temperature in all cases was less than the traditional wall temperature due to the added element of PCM. According to Fourier equation, heat flux is generated in the wall layers due to the absorbed radiation at external layer, which is directly proportional to the temperature difference, the thermal conductivity of the wall layers, and the wall area, and inversely with the thickness of the wall.

It can be noticed from Fig. 8 that the temperature curve increases slowly for the first hour because of the time lag. The time lag happens due to the multiple resistance layers of the wall that suppress the travel of heat toward the internal surface lower temperature. After four hours of continuous heating the internal surface temperature of the RW, C1, and C2 walls were at 23.1°C , 20.5°C , and 20.76°C respectively. The temperature continues rising even after the heat source was turned off, as shown in the Fig. 8 because of the stored heat in the wall layers and the time lag. After two hours of the cooling period, the internal surface

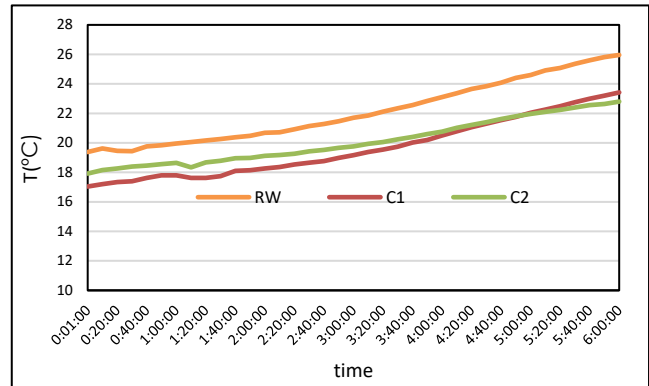


Figure 8. Comparison of interior wall surface temperatures T_{si} variation for walls samples with the reference wall sample.

temperature reached its maximum, the RW, C1, and C2 walls' temperature were equal to 25.96°C , 23.42°C and 22.8°C respectively.

The table 2 below shows the heat flux calculation which was generated in the wall layers at the end of the heating period. The highest heat flux was at the traditional wall and was equal to 33.8 W . while the minimum heat flux was at C2 and was equal to 21.7 W , which is the optimum case.

Table 2: Heat flux at maximum external surface temperature for radiation: 900 W/m^2

	$T_{se} (^{\circ}\text{C})$	$T_{si} (^{\circ}\text{C})$	$\Delta T (^{\circ}\text{C})$	$Q (\text{W})$
RW	73.8	23.1	50.7	33.8
C1	63.02	20.5	42.52	26.6
C2	55.42	20.76	34.66	21.7

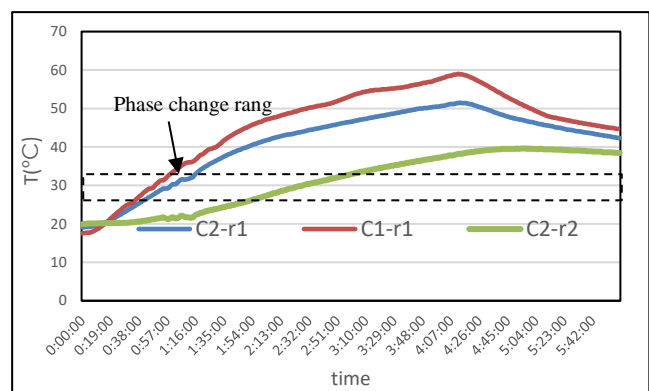


Figure 9. Comparison of the temperature of the first row of paraffin in C1 and C2, and the second row of C2.

The paraffin temperature curve of the experiments conducted for C1 and C2 as shown in Fig. 9. The C1-r1 and C2-r1 curves represent the PCM temperature in the first row of C1 and the first row of C2. While C2-r2

represent the PCM temperature in the second row of C2. The initial temperature of the thermocouples attached to the capsule was reading 17.5°C, 19.1°C and 19.9°C for C1-r1, C2-r1 and C2-r2 respectively. It took more than one hour for the PCM temperature to reach 38 °C in C1-r1, 38.1°C in C2-r1, and 37.3°C in C2-r2. After the heating period of four hours reached to end, the paraffin temperature was equal to 57.7°C, 50.6 °C, and 39.5°C in C1-r1, C2-r1, and C2-r2 respectively. Which means that the paraffin was melted totally when the external surface temperature reached its maximum in both C1-r1 and C2-r1 and partially in C2-r2.

4. Conclusion

In this paper, practical experiments were made on different models of wall parts grafted with phase changing material. Macro capsule filled with paraffin were embedded with the perforated bricks. The results of comparing the different wall models thermal behavior can be summarized by the following points:

- The heat flux passing through the layers of the wall when radiating an amount of 900W/m² was equal to 33.8, 26.6, and 21.7 W for each of the RW, C1, and C2 respectively. After four hours of heating.
- C2 wall was optimal since it has a lesser amount of heat flux which was calculated at the maximum external surface temperature for each amount of radiation.
- The lowest temperature of the internal wall surface of sample C2 was recorded compared to the reference wall where the difference was more than 3 °C. While in C1 the difference was 2.5 °C less than the reference wall.

The energy storage of the paraffin used in the experiment for each of the C1 and C2 walls were equal to 261kJ and 522kJ, respectively

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