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Thermal performance of latent heat storage: Phase change material melting in horizontal tube applied to lightweight building envelopes

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ABSTRACT

This paper focuses on the experimental investigation of the storage and release of thermal heat during melting and solidification of PCM (phase change material). The materials tested have a gypsum or epoxy resin matrix which incorporates metallic tube filled with PCM. An investigation by means of a differential scanning calorimeter (DSC) was carried out to obtain the latent heat and the transition temperature of paraffin. The main objective is to elucidate which is the most efficient composite-PCM by measuring, effective thermal conductivity, total heat accumulated; the average heat capacity and latent heat stored using a new transient hot plate apparatus. Comparing the results, it was demonstrated that that the considered composite gypsum-PCM has potential thermal energy storage purpose in buildings.

Experimental investigations of the thermophysical properties of the considered composite (gypsum/copper tubes) have shown that the material combines a high heat storage potential and an improved heat transfer at the same time. Besides, the results showed that the shape-stabilized phase change material prevents the leakage of the molten paraffin during phase transition and proved a good thermal stability.

1. Introduction

Energy consumption in buildings still represents the most important percentage of energy applied in most developed and developing country‘s electricity supply for various types of building services systems [1]. Current statistics on energy show that 85% of a building’s gas emissions is created by cooling, heating and lighting activities [2,3].

The use of phase change materials (PCMs) in buildings is contemplated as an effective innovative technology for reducing energy consumption and has gained more and more attention. Paraffinic PCMs are measured as the most promising candidates and has been commonly used in building thermal energy storage applications because of their many desirable properties: good thermal and chemical stability, high latent heat, abundance and low cost, low vapor pressure, noncorrosive and nontoxic properties [4–6]. The inconvenience of paraffin is its low thermal conductivity and leakage, which can hinders its extensive applications. It extends the period of charging and discharging process of the thermal energy storage and can reduce the rate of storing and releasing energy of PCM.

For over three decades, research projects investigated several techniques for enhancing the thermal storage of the PCM. The most common techniques are:

- Increasing the heat transfer area either by, using heat pipes [7], application of multi-tubes heat exchangers [8], or utilization of finned tubes [9].
- Improving the PCM thermal conductivity either by dispersing high conductivity particles within the PCM [10,12–14], inserting a metallic matrix into the PCM, utilizing of bubble agitation in the PCM [11] and impregnating a porous graphite matrix with PCM [15,16].

The latent heat storage capacity of PCMs is important although the limitation factor to stimulate this heat is their very low thermal conductivities that obstruct from efficient utilization of these materials [35]. Many research studies have been conducted on enhancement of thermal conductivity of phase change materials. Several recent works that adopt this approach can be cited. As an example, Moussa et al. [36], have conducted an experimental and numerical study about the storage and release of thermal heat during melting and solidification of PCM. The material used for

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Nomenclature

e	composite width	*Subscripts*	
t	times	1, 2	lower and higher face of the composite
ρ	density of composite, kg m^{-3}	*init*	initial thermal steady state
T	temperature, °C	*end*	final thermal steady state
C_p	specific heat capacity, kJ/kg °C	*sens*	sensible
λ	thermal conductivity, W m^{-1} K^{-1}	*s*	solid state
Q	energy per mass stored, J/g or kJ/kg	*l*	liquid state
L	latent heat of fusion (kJ/kg)	*m*	melting
φ	density of heat flux, W/m^2	*c*	crystallization

thermal energy storage systems is a composite based on epoxy resin loaded with metal hollow tubes filled with paraffin wax. Their study has shown a good improvement in the thermal conductivity (about 3–4 times higher than the pure PCM). Results also exhibited that the higher the PCM content, the higher the energy storage capacity of the sample and the lower the temperature gradient variation. In the same context, Lachheb et al. [18], investigated the thermal performances of a new integrated component (gypsum + copper tube filled with paraffin wax) in a passive solar wall. The test showed a comprehensible enhancement in different thermal properties of the PCM. As a result, they found out that the composite PCM impeded the leakage of the molten paraffin during phase transition and proved an excellent thermal stability due to the effect of copper tube. On the other hand, Lidia Navarro et al. [37] studied the thermal performance of a prefabricated concrete slab with PCM macroencapsulated in small metallic tubes and inserted in its hollows. The integration of a mesh of metallic tubes filled with PCM inside the hollows enhances the heat exchange between the PCM and the air. The test results revealed that an important amount of energy demand covered by the PCM storage.

Studies into composite PCM drywall systems particularly gypsum board is a quite recent research subject. Gypsum board is usually found in the interior walls or ceilings due to its easy fabrication features, excellent fire resistance properties, environmental friendliness, esthetics. In addition, it presents low prices and can be carried out in situ or as precast slabs. [17]. Therefore, such enormous potential has led to past efforts in the direction of the development and the thermal characterization of PCM gypsum board.

For instance, Borreguero et al. [19] carried out the feasibility of incorporating microcapsules containing PCMs in gypsum boards to improve the wall energy storage capacity. It was revealed that the composite PCM gypsum boards were competent to either enhance or reduce the average surface temperature by up to 1.3 °C respectively during the melting and cooling processes. Darkwa and Kim [20] investigated experimentally the thermal performance of laminating microencapsulated hexadecane phase change material (HPCM) and randomly mixed PCM into gypsum board. They affirmed that it is possible to develop such materials for enhancing and minimizing heat transfers in drywall systems.

Moreover, heat transfer enhancement search was performed by Darkwa and Zhou [21]. They developed a laminated composite aluminum/hexadecane gypsum board and compared it with a pure hexadecane gypsum board sample. The test results showed more rapidly thermal response by the aluminum/hexadecane sample concerning the rate of heat flux and as well achieved about 10% and 15% heat transfer enhancements during the storing and releasing periods. In addition, thermal conductivity also increased by 1.25 W/m K as compared with 0.15 W/m K for pure hexadecane sample. Nevertheless, fairly lower energy storage density was found due to the elevated porosity of the microencapsulated PCM powder.

A new construction element has been studied [22]: a shape-stabilized PCM either as a sheet or as pellets was introduced into gypsum board. The work is specially intended to characterize its thermo-physical proprieties. The results demonstrated that the gypsum containing PCM is more thermally insulating than the gypsum without PCM. On the other hand, it showed that the average heat capacity (Cp sample) of the samples containing sheet-PCM and pellets PCM are greater to the gypsum by itself due to the latent heat effect, being 41% and 33% respectively. PCM have been integrated in different matrixes as cement, gypsum, mortar, polymeric matrix, etc. in order to enhance the thermal energy storage capacity of the building walls as passive system.

The goal of this paper is to improve thermal properties of a construction material that has a low thermal conductivity. To increase the thermal conductivity we will employ hollow tubes. This choice is based on a work that was already published [26] which shows that the center of the solid tube is not important to improve heat conductivity, so it can be filled with another material (PCM) and incorporated in another matrix which is more applied and utilized in the sector of building, then we can improve conductivity and on the same time we increase the thermal storage quantity per unit of mass.

The present work aims at developing new construction material for utilize in high-comfort constructive and to contribute to elucidating our knowledge and understanding of the effects of the PCM incorporated in building material. This material consists of copper tubes filled with HPCM which are regularly spaced and aligned in a gypsum matrix. The prepared composite shows features of high energy storage density, a high thermal conductivity of heat exchange, and an absence of molten paraffin leakage. This paper is focused on the experimental investigation of the thermal energy storage properties improvement of a new composite PCM. The melting temperature, latent and sensible specific heat of the PCM was characterized using DSC (differential scanning calorimetry). The thermophysical properties of the elaborated material have been measured using Transient Guarded Hot Plate Method (TGHPM). The results of the experimental investigation will be compared with the experimental results obtained by Trigui et al. [26] and thus serve to validate the present experimental approach. From the obtained results, it can be concluded that the considered composite based gypsum loaded with metal hollow tubes filled with HPCM has potential thermal energy storage purpose in buildings.

2. Experimental study

2.1. Materials

PCMs, in cooling/melting temperature range of 19 °C and 22 °C, have been contemplated appropriate for the free cooling application of buildings. In this study, Hexadecane, $C_{16}H_{34}$ was chosen as the HPCM liquid based on its high latent heat and suitable phase change temperature, which is in the range of human comfort temperature. Hexadecane is a saturated hydrocarbon of the alkenes