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Experimental and numerical investigation for improving the thermal performance of a microencapsulated phase change material plasterboard

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ABSTRACT

The energy storage in buildings is a significant means for an optimal management of thermal energy. The use of phase change materials in a building envelope can improve heat storage capacity and the thermal behavior of the wall. However, the small thermal conductivity of the phase change materials slows down the process of heat absorption and release. The present study suggests a new technical solution for improvement of thermal behavior of a phase change material plasterboards. It consists of perforating the panel with several small holes yielding a greater contact surface area with the surrounding air. This passive enhancement technique is implemented experimentally and numerically to check its performance. Results show that the perforated panels produces an augmentation in heat absorption and release. The average increase was 100% for heat absorption and 175% for heat release as compared to a standard panel without holes. In addition, a perforated panel with a given thickness can absorb heat as much as a standard panel three to four times thicker. Furthermore, it was found that the absorbed and released heat flux values have a direct relationship with the ratio of the panel thickness to the holes spacing.

1. Introduction

The building sector is considered as a major consumer of energy. Its consumption represents 25% of the total energy consumption in the world which makes it the third largest consumer of energy after the industry sector (32%) and the transport sector (31%) in 2010, according to the statistics of the International Energy Agency (IEA) [1]. In another work published by Waqas and Din [2], it is reported that the building sector alone is responsible for about 30–40% of the primary energy consumed annually in the world and is also responsible for one third of the greenhouse gas emissions.

The use of energy efficiency measures in buildings has become necessary to estimate the energy needs in the residential sector. The energy consumption is mainly due to the use of heating and air conditioning to improve the thermal comfort inside the dwellings. This energy generated by the heating or the air conditioning appliances will be lost later either by transmission through the envelope of the dwelling or by renewal of air. Therefore, energy storage is a convenient means for an efficient and optimal management of thermal energy. It allows adapting production to the energy needs and create the most favorable conditions for this management by achieving a continuous relationship between the energy demand and the supplied energy.

A literature survey shows that an important number of experimental and numerical studies about the use of Phase Change Materials (PCM) for storage of latent heat in buildings have been undertaken during the recent years [3]. The use of PCM in the building can help improve thermal comfort by increasing the thermal inertia of the building walls [4]. Indeed, PCM are capable of absorbing, storing and releasing large amounts of energy as latent heat in a relatively small temperature range following a phase change [5]. The heat storage and release yield reduction of energy consumption by storing energy in the PCM during the day (when the air temperature is high) and releasing it during the night (when the air temperature is generally low) [6]. There are two types of thermal energy storage system, the active storage systems who is characterized by using systems to create a forced convection heat transfer into the storage material [7]. However, the passive storage systems do not require any additional heat exchanger to extract heat from the storage. This system uses the thermal mass of the building to store energy in building envelopes in the form of latent heat [8].

Other studies have reported on PCMs as a very good way to improve thermal inertia of materials for lightweight buildings [9]. Among these studies, Kuznik et al. [10] showed in their study that a 5 mm thick PCM plasterboard with 60% micro-encapsulated paraffin, whose melting temperature is 22 °C, can store an amount of energy equivalent to 8 cm

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Nomenclature

Latin letters

A_i	area of air passage for one hole (m^2)
A_p	area of panel (m^2)
A_T	total area of air passage (m^2)
$C_{p.air}$	specific heat of air ($J\,kg^{-1}\,K^{-1}$)
C_{pm}	specific heat of material ($J\,kg^{-1}\,K^{-1}$)
D	distance between two holes (m)
g_j	gravitational force vector (–)
H	specific enthalpy ($J\,kg^{-1}$)
L	length of the panel (m)
$\dot{m}_{air}$	air mass flow rate ($kg\,s^{-1}$)
n_i	number of holes (–)
P	static pressure (Pa)
S	energy source term ($W\,m^{-3}$)
T	temperature (K)
t	time (s)
$u_{i,\,j}$	velocity components (–)
v	velocity ($m\,s^{-1}$)
$x_{i,j}$	direction vectors x, y (m)

Greek letters

λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
φ	heat flux density ($W\,m^{-2}$)

Subscripts

ab	absorption
aver	average
exp	experimental
f	freezing
inp	input
int	interior air
liq	liquidus
m	melting
mea	mean air
num	numerical
out	outlet
sol	solidus
t	current time
t − 1	previous time

thick concrete.

To be chosen as a good candidate, a PCM must satisfy the following requirements: the melting temperature range has to fit the application, high latent heat of melting, high thermal conductivity, easily available and low cost and stable thermal and chemical properties [11]. The determination of thermophysical properties of the PCM, mainly thermal conductivity, latent heat capacity, temperature of melting and density, is an important step in the process of thermal management by assessment of energy saving performance of PCM composites (plaster-PCM, concrete-PCM, etc.). The thermal properties are of major importance in the thermal behavior of a wall incorporating a PCM, since the performance of these walls depends essentially on their principal thermophysical properties. Studies have been carried out to determine experimentally, numerically and even analytically thermophysical properties of PCM plasterboards. Among these works, Porfiri et al. [12] who developed an analytical model to predict the thermal conductivity of composites using homogenization techniques. The model was validated with finite element analysis (FEA). It was observed that the thermal conductivity values predicted by the analytical model match closely the results determined by FEA. This study remains without experimental validation.

Several studies have been undertaken in order to improve the absorption and release of heat for walls incorporating a PCM. The ultimate aim of these studies was to develop new ways to increase the thermal conductivity of the PCM leading to a better heat absorption by conduction thus improving the efficiency of heat storage energy systems [13]. The low thermal conductivity of the PCM, of the order of 0.2 W/m K on average, is a drawback for storing or releasing energy and limits its applications [14]. There are two ways of enhancing thermal conductivity: the first one is to add substances whose thermal conductivity is higher than that of the PCM and the second is to encapsulate the phase change materials [11]. Among the studies that proceeded by the first way, Şahan et al. [15] in their work to enhance the thermal properties of a paraffin, a nano-magnetite (Fe_3O_4) was mixed homogeneously into paraffin by a dispersion technique at two different mass fractions (10% and 20%). The results found showed that the thermal conductivities were increased by 48% and 60%, respectively. For the second way, Dao and Jeong [16] used graphene to encapsulate Stearic Acid (SA). The maximum thermal conductivity found for the composite prepared with 5 phr graphene by solution mixing method increases to 126% that of stearic acid.

Another alternative is to improve the heat transfer by convection on the PCM surface in order to complete the charge-discharge cycle, as several researchers concluded it. Koo et al. [17], found in their study that the thermal heat storage of a PCM plasterboard increased with the convective heat transfer coefficient. And in the same frame, David et al. [18] developed in their study a numerical model to evaluate several convective heat transfer correlations from the literature. Their model concerned natural, mixed and forced convection flows. The results found show that the convective heat transfer have a high impact on the storage/release process in the case of PCM plasterboards. For the case of natural convection, the results are highly dependent on the correlation used during the numerical study and the results may vary up to 200%. For the mixed and forced convection flows, the higher the velocity, the more important is the storage capacity. In 2016, the same researchers [19] investigated the effect of the phase change on the heat transfer by natural convection along the PCM wallboard and the rate of energy storage by PCM with different air velocities and ambient temperatures. On this study, it is found that the phase change causes an increase in the convection heat flux. It is characterized by three consecutive stages: a first dynamic stage, a wall surface temperature slowdown/retrogression and a second dynamic stage. In the same approach, a new correlation was established by Gracia et al. [20] for the convective heat transfer coefficient between an airflow and a plate made up of phase change material (PCM). Indeed, the results obtained with the correlation show better agreements with the CFD simulation results, which made this correlation more suitable for the simulation of the PCM heat storage systems. The studies of David et al. [18,19] and Gracia et al. [20] reported only on the influence of the convective heat transfer coefficient and the airflow on the thermal behavior of a panel including a phase change material.

The aim of the present work is to contribute with a technical solution to improve the heat transfer of a PCM plasterboard without changing the physical characteristics of the PCM. This technical solution consists of perforating the panel with several small holes to allow air flowing through them during the ventilation of the house. This technique yields an increased heat transfer surface area between the panel and air, leading to a higher convection heat absorption and release around the PCM plasterboard. The operating principle of the use of perforated PCM plasterboard for improving the heat absorption and