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Simulation of phase change drywalls in a passive solar building

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Abstract

Integration of phase change materials (PCMs) into building fabrics is considered to be one of the potential and effective ways of minimizing energy consumption and CO_2 emissions in the building sector. In order to assess the thermal effectiveness of this concept, composite PCM drywall samples (i.e. randomly-mixed and laminated PCM drywalls) have been evaluated in a model passive solar building. For a broader assessment, effects of three phase change zones (narrow, intermediate and wide) of the PCM sample were considered. The results showed that the laminated PCM sample with a narrow phase change zone was capable of increasing the minimum room temperature by about 17% more than the randomly-mixed type. Even though there was some display of non-isothermal phase change process, the laminated system proved to be thermally more effective in terms of evolution and utilization of latent heat. Further heat transfer enhancement process is however required towards the development of the laminated system.

Keywords: Phase change material; Phase change zone; Heat transfer

1. Introduction

Passive architecture can be interpreted as architecture which tempers the external environment in order to create a relatively stable environment internally. Therefore, a passively designed building incorporating such features as exposed walls, ceiling and floor slabs with energy storage capabilities could help stabilize the internal environment and thus minimise energy consumption. Integration of phase change material (PCM) into building fabrics have been discussed and reported as potential method of reducing energy consumptions in passively-designed buildings [1–6]. The characteristics of PCMs make them inherently suitable for use for energy conservation purposes without the complications brought about by other thermal storage devices requiring separate plant and space.

Although the principles of latent heat storage can be applied to any porous building material, most PCM research work have been concentrated on integration with gypsum wallboard and concrete blocks. For instance experiments have been carried out by Feldman et al. [7] and found gypsum wallboard to be compatible with a broad range of PCMs, including fatty acids and esters. Studies conducted by Athientis et al. [8] showed that an integrated PCM wall board could reduce the maximum room resultant temperature in a passive solar building by up to 4 °C during the daytime and also significantly reduce the heating load at night.

With respect to thermal comfort criteria, Lamberg et al. [9] have investigated the effects of integrated PCM concrete structures. Even though there was the recognition for a mechanical ventilation system to improve upon poor heat transfer rates, considerable improvement in indoor temperature was noticed.

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Nomenclature

A	area (m^2)
C	specific heat capacity (J/kg K)
I	intensity of solar radiation (W/m^2)
N	number of air changes (Ac/h)
Q	heat (W)
U	U-value (W/m^2 K)
V	volume (m^3)
T	temperature (°C)
t	time (s)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
ρ	density (kg/m^3)
τ	transmission coefficient through glass

Subscripts and superscripts

eff	effective
g	glazing
i	initial
j	nodal point
L	latent
l	liquid phase
m	melting phase
r	a room air
s	solid phase
w	wall
su	sundry

Darkwa et al. [10–13] have analytically and experimentally evaluated two integrated gypsum-based PCM systems (i.e. randomly-mixed and laminated PCM systems) and found the thermal performance of the laminated-PCM system to be about 18% better than the randomly-mixed type. However these studies were limited to narrow boundary conditions and assumptions. The present study is therefore intended to simulate the practical performance of both the randomly-mixed and laminated PCM systems in a passively-designed model room.

2. Model room description

Fig. 1(a) shows a diagram of the model room measuring 3 m × 4 m × 2.5 m high. It also has one window measuring 1.5 m × 1 m and facing south. The walls are of lightweight construction with the interior surfaces lined with 12 mm thick PCM wallboard. Both drywall samples contain the same amount (16.7 mass%) of PCM but the laminated sample (Fig. 1(b)) consists of 2 mm and 10 mm separate layers of PCM and gypsum respectively whilst the randomly-mixed type (Fig. 1(c)) is made up of one layer of PCM and gypsum mixed together.

3. Mathematical modelling

3.1. Energy equations for PCM wall boards

The equations presented here are based on previous studies by Darkwa et al. [9,10] as follows:

For the randomly-mixed type, a three-dimensional energy equation was considered as

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=\rho\frac{\partial H}{\partial t}=\rho\frac{\partial}{\partial t}\int C_{\mathrm{eff}}\,\mathrm{d}T. \tag{1}$$

The laminated type was reduced to one-dimensional energy equation as

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)=\rho\frac{\partial H}{\partial t}=\rho\frac{\partial}{\partial t}\int C_{\mathrm{eff}}\,\mathrm{d}T, \tag{2}$$

where H is the enthalpy and expressed for isothermal phase change process as

$$H(T)=\int\rho C_{\mathrm{eff}}(T)\,\mathrm{d}T. \tag{3}$$

For phase change process over an interval of T_{s} to T_{l}, the enthalpy is expressed as

$$H(T)=\int_{T_{\mathrm{j}}}^{T_{\mathrm{s}}}\rho C_{\mathrm{s}}(T)\,\mathrm{d}T+\int_{T_{\mathrm{s}}}^{T}\left[\rho\left(\frac{\mathrm{d}Q_{\mathrm{L}}}{\mathrm{d}T}\right)+\rho C_{\mathrm{m}}(T)\right]\mathrm{d}T\ (T_{\mathrm{s}}<T\leqslant T_{\mathrm{l}}), \tag{4}$$

$$H(T)=\int_{T_{\mathrm{j}}}^{T_{\mathrm{s}}}\rho C_{\mathrm{s}}(T)\,\mathrm{d}T+\rho Q_{\mathrm{L}}+\int_{T_{\mathrm{s}}}^{T_{\mathrm{l}}}\rho C_{\mathrm{m}}(T)\,\mathrm{d}T+\int_{T_{\mathrm{l}}}^{T}\rho C_{\mathrm{l}}(T)\,\mathrm{d}T\ (T\geqslant T_{\mathrm{l}}). \tag{5}$$

Now by considering identical properties for both liquid and solid phases the effective heat capacity can be, written in the Gaussian format as

$$C_{\mathrm{eff}}=C_{\mathrm{s}}+a\mathrm{e}^{-0.5\left(\frac{T-T_{\mathrm{m}}}{b}\right)^2}, \tag{6}$$

where a is the total amount of latent heat and b is the width of phase change zone.