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Thermal response of brick wall filled with phase change materials (PCM) under fluctuating outdoor temperatures

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ABSTRACT

Based on the enthalpy-porosity technique, a model of thermal conduction accompanied with solidification and melting processes is developed and numerically analyzed to investigate the thermal response of the brick wall filled with phase change materials (PCM). The thermal response, which is represented by indoor wall surface temperature response, of brick wall filled with PCM is evaluated and compared with that of solid brick wall. The effects of PCM filling and its filling amount on thermal response of brick wall are investigated and discussed. It is indicated that, compared to the common solid brick wall, the thermal storage of brick wall filled with PCM is elevated by the alternate process of melting and solidification under fluctuating outdoor temperatures. The use of PCM in the brick walls is beneficial for the thermal insulation, temperature hysteresis and thermal comfort for occupancy. In addition, with the increasing filling amount of PCM, the fluctuation of indoor wall surface temperature is significantly smoothed. Correspondingly, the hysteresis in response to the outdoor temperature fluctuation is enhanced. Moreover, the present model is verified by experimental data available in the literature.

1. Introduction

As low carbon and green economy is becoming as a part of national global warming mitigation strategy, the phase change materials (PCM) has been introduced as an attractive option to building wall materials for building energy conservation and cost saving of HVAC systems due to their potential latent heat thermal storage [1–7]. The investigation of building wall with phase change materials is of considerable interest in the past several years [8].

Feldman et al. [8] tested the thermal performance of PCM mixed from methyl palmitate (MeP) and methyl stearate (MeS) using DSC (differential scanning calorimetry). This type of PCM has a melting-freezing interval of approximately 23–26.5 °C, which is suitable for hot climates. Farid et al. [9] reviewed the previous work on latent heat storage and provided an insight to develop new materials. A variety of materials including organic and inorganic, especially microencapsulated PCM were evaluated and compared. Xiao et al. [10] studied the preparation and performance of shape stabilized phase change thermal storage materials. It was indicated that shape stabilized PCM made of paraffin and SBS (styrene-butadiene-styrene) almost has the same thermal properties as pure paraffin, and the thermal conductivity of shape stabilized PCM increases as the introduction of expanded graphite. Lv et al. [11] carried out the thermal cycle tests to study the thermal properties in latent heat of melting and freezing temperature of wallboards combined with the eutectic mixtures of CA (capric acid) and LA (lauric acid) through DSC. This experiment proved that these phase change wallboards have good thermal stability for melting temperature and variations in latent heat of fusion for long time application. Cabeza et al. [12] conducted experiments to investigate thermal properties of a new innovative concrete with PCM microcapsule and tested the energy saving performance of cubicles with it. The results showed that PCM microcapsule leads to an improved thermal inertia as well as lower inner temperatures. It should be noted that, although a great progresses has been obtained in the thermal performance test of phase change material, great differences still exist among the available research due to the complexity and variety of PCM.

Apart from the thermal performance test of single phase change material, plenty of experimental works have also been done to understand the thermal response of the rooms including PCM wallboards owing to the fact that most energy conservation systems utilized wallboards impregnated with PCM. Lv et al. [13] constructed a PCM wallboard room sized 5 m × 3.3 m × 2.8 m to test the room temperature and energy consumption. It is indicated that the energy consumption is effectively reduced and the electric load can be shifted to off-peak periods by the use of PCM. Frédéric and Joseph [14] experimentally investigated the thermal performance of a full scale test room with PCM copolymer composite wallboards by repeating a typical day including temperature and solar radiative flux via totally control climate simulation, and found

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Nomenclature

A	fluctuation amplitude of temperature
a	solar radiation absorptivity of a surface
c	heat capacity
f	decrement factor
h	enthalpy
I	global solar irradiance
L	length
L_p	latent heat
T	temperature
x, y	axial coordinate
Subscript	
b	brick solid matrix
i	iteration numbers
in	indoor
l	liquid
$sol\text{-}air$	sol-air
out	outdoor
p	phase change material
s	solid
Greek symbols	
α	convective heat transfer coefficient
β	liquid fraction
δ	porosity
τ	time
ρ	density
λ	thermal conductivity

that the thermal comfort of test room is enhanced by the use of PCM. Additionally, there is a few numerical simulation of the thermal performance of PCM wallboards systems. For example, Halawa et al. [15] presented a numerical analysis of PCM thermal storage unit consisted of layers PCM slabs with varied air temperature.

To sum up, the available investigation on the brick wall with PCM is still limited at the start-up period, and mainly focused on the development and preparation [8–11] and experimental performance evaluations of PCM wallboards [13,14]. There is relatively little work on the theoretical prediction of the dynamic heat transfer processes of brick wall filled with PCM, especially the thermal conduction accompanied with melting and freezing processes under fluctuating temperatures.

For a long time, the geometric characterization of brick wall is an important challenge to model the dynamic heat transfer process of brick wall. Conventionally, the geometry of PCM brick wall is in the form of slabs or microcapsules, which is difficult to reflect the effect of pore configuration of brick wall. Fortunately, the self-similar Sierpinski carpet has found to be an appropriate tool to simulate the porous brick wall due to the following typical features [16]: (1) Pores are of different sizes, and different porosity with similar structure can be obtained via circulation iteration; (2) Pores are in the discrete distribution and no connections exist among the pores; (3) The solid matrix can meet the load requirements.

Therefore, in the current study, Sierpinski carpet is introduced to characterize the geometric structure of brick wall filled with PCM. Based on this structure characterization, a model for thermal conduction accompanied with solidification and melting is developed and numerically analyzed to investigate the thermal response of the brick wall filled with PCM under fluctuating temperatures. The effects of PCM amount as well as spatial distribution of PCM on the dynamic heat transfer characteristic of the brick wall are all investigated and discussed. In addition, the thermal insulation performance of brick wall is evaluated and compared with that of the common solid wall.

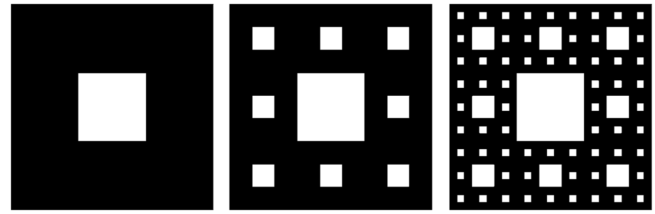

Fig. 1. Schematic of Sierpinski carpet.

2. Geometric construction of brick wall

The Sierpinski carpet [16], as shown in Fig. 1, is a typical self-similar porous fractal object. Its generation algorithm is: begins with a square, the Sierpinski carpet is constructed following the principle of dividing the square into 9 congruent subsquares and removing the central one then repeating the same procedure recursively to the remains, and infinitum. The fractal dimension of Sierpinski carpet $D = \ln 8/\ln 3 = 1.893$. For the ith recirculation, the porosity and pore scale of the Sierpinski carpet can be calculated as

$$\varepsilon_i = 1 - \left(\frac{3^2 - 1}{3^2}\right)^i \tag{1}$$

$$L_i = \frac{L_0}{3^i} \tag{2}$$

For the iteration numbers $i = 1, 2, 3$, the corresponding porosities are 0.111, 0.209 and 0.298, respectively.

Considering the length and width of the real building brick walls are much larger than their thickness, to simplify the calculation, only the temperature variations along the thickness direction are considered, i.e. a two dimensional heat transfer in brick wall is investigated. The hollow brick wall is a typical porous object. It has been confirmed that [17], the Sierpinski carpet is an effective method to characterize porous object so as to investigate the thermal transport performance. In this context, the Sierpinski carpet is applied to simulate the unit of brick wall in this paper. Since the PCM is directly filled in the pore, the filling amount of PCM can be directly represented by the porosity of the Sierpinski carpet.

As a latent thermal energy storage building material, the appropriate PCM should be adopted in certain climate so as to ensure the dynamic heat transfer process accompanied with solidification/melting progress happened under fluctuating outdoor temperatures. In this paper, the materials of solid matrix is assumed to be common brick, and the PCM is assumed to be a mixture of $Mn(NO_3)_2{\cdot}6H_2O$ and $MnCl_2{\cdot}4H_2O$, and the thermal properties are presented in Table 1.

3. Mathematical model

3.1. Governing equations

The brick wall filled with phase change materials (PCM) can enhance thermal insulation in building envelop by the ability of heating and cooling storage based on the melting and solidification

Table 1
Thermal properties of materials.

	ρ (kg m^{-3})	c (J kg^{-1} K^{-1})	λ (W m^{-1} K^{-1})	L_p (kJ kg^{-1})
Brick [11]	1560	920	0.49	
PCM [7]	1700	2500	0.6	125.9