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Indicators evaluating thermal inertia performance of envelops with phase change material

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ABSTRACT

Phase change material (PCM) has been widely integrated in building envelops to increase their thermal inertia performance. To evaluate the thermal inertia performance of materials and envelops, Chinese Thermal Design Code has provided three indicators, namely, thermal storage coefficient, thermal resistance and thermal inertia index. The existing simplified method calculating the thermal storage coefficient is only applicable for materials with constant thermal properties. For those with varying thermal properties, such as PCM, however, further developments are still required. To solve this issue, both dimensional analysis and numerical simulation were carried out to develop relationships between the thermal storage coefficient of PCM and its other thermal properties (e.g. thermal conductivity, density and the effective equivalent specific heat). Based on the developed relationships, a simplified method calculating the thermal storage coefficient of PCM was proposed in this study. This simplified method was then combined into the thermal inertia index for evaluating the thermal inertia performance of building envelops with PCM.

1. Introduction

Phase change material (PCM) has been widely integrated in building envelopes [1–5], thanks to its ability of increasing the thermal inertia performance of building components [6–9], hence improving indoor thermal comfort [10–14]. In the past several decades, many studies have been carried out to explore the effectiveness of PCM on improving indoor thermal comfort in buildings [15–18]. Ling et al. [15] explored this in solar greenhouses with and without PCM, using both experimental and numerical methods. From the study, they confirmed a significant contribution of PCM to enhancing the indoor thermal environment under different weather conditions and over a long time, with a maximum increasing rate of 15.3% for the daily effective accumulative temperature. Shi et al. [16] presented results from an experimental investigation on macro-encapsulated PCM that has been incorporated in concrete walls in real rooms, and they found out that the maximum temperature and the relative humidity were decreased by up to 4 °C and 16%, respectively, in the room with PCM, comparing to that without PCM. Castell and Farid [17] assessed the effectiveness of using PCM in passive cooling building envelopes. From the study, they reported that the building with PCM had a lower risk of thermal discomfort, and this result was supported by Evola et al. [18].

Existing studies on the thermal inertia performance of building envelops focused on evaluating their ability with respect to both heat storage and thermal insulation. Ling et al. [15] developed an one-dimensional unsteady numerical heat transfer model for calculating the daily heat storage of external walls with PCM in solar greenhouses. They reported that PCM provided a great contribution to the overall thermal storage of the wall (the daily heat storage rate of PCM during daytime on sunny and cloudy days were 78.1% and 80.3%, respectively). Zhou et al. [19] carried out a thermal evaluation of a non-deform laminated composite gypsum board that consists of a 4 mm PCM layer in a naturally ventilated condition, and they figured out that the maximum energy storage reached to 363.7 kJ/m^2. In mid-western Greece, Mandilaras et al. [20] have built a two-storey typical family house with PCM in the external walls. Their experimental data reflected that the thermal insulation performance of the walling system was promoted in late spring, early summer and autumn, due to the use of PCM. Additionally, the

Abbreviations: PCM, phase change material; EVAC, ethylene vinyl-acetate copolymer.

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Nomenclature

C	Constant
c	Specific heat capacity (J/kg °C)
D	Thermal inertia index
k	Thermal conductivity (W/m °C)
kg	Dimension of mass
m	Dimension of length
q	Heat flux (W/m^2)
R	Thermal resistance (m^2 °C/W)
s	Dimension of time
t	Temperature (°C)
TSC	Thermal storage coefficient (W/m^2 °C)
x	Independent variable
y	Variable
Z	Periodic time of the heating effect (s)
ρ	Density (kg/m^3)
δ	Thickness (m)
τ	Time (s)
°C	Dimension of temperature
Δh	Enthalpy difference (kJ/kg)
Δt	Temperature difference (°C)

Subscripts

Br	Brick
i	Node position or serial number
In	Polystyrene board
max	Maximum
min	Minimum
n	Serial number
PCM	phase change material
sum	Sum
wall	Wall
wall, in	Inner surface of wall
wall, out	Outer surface of wall

Superscript

j	Time coordinate

decrement factor decreased by a further 30–40% and the time lag increased for about 100 min. Zhou et al. [21,22] have investigated both temperature wave and heat flux wave on the inner surface of shape-stabilized PCM wallboards with sinusoidal temperature wave and heat flux wave on the outer surface, and compared the results with those from conventional building materials such as brick and foam concrete. From both investigations, they found out that PCM wallboards provided the longest time lag and the lowest decrement factor.

To evaluate the thermal inertia performance of materials and envelops, Chinese Thermal Design Code for Civil Buildings (GB 50176-201X) [23] has provided three indicators, namely, thermal storage coefficient, thermal resistance and thermal inertia index. Wang et al. [24], Kong et al. [25] and Feng [26] have adopted these indicators when evaluating the thermal inertia performance of building envelops made of materials with constant thermal properties. To estimate the thermal storage coefficient, a simplified calculation method has been given in the standard. For materials with constant thermal properties, e.g. soil and cement mortar, this method can be attained using Laplace transform [27]. However, for PCM that has changing equivalent specific heat capacity during the phase change process [28,29], its thermal storage coefficient can't be estimated using the current method provided.

This study is aiming to further develop the existing simplified calculation method in the Chinese standard for estimating the thermal storage coefficient for materials with changing thermal properties, focusing on PCM. In the study, relationships between the thermal storage coefficient of PCM and its other thermal properties (e.g. thermal conductivity, density and effective equivalent specific heat) were developed using the Rayleigh's method of dimensional analysis. Additionally, the thermal storage coefficient of PCM with different thermal properties was predicted by EnergyPlus [30], a popular dynamic building performance simulation tool. Combining results of both dimensional analysis and numerical simulation, an updated simplified method calculating the thermal storage coefficient of PCM was proposed. Finally, a case study using this updated method to evaluate the thermal inertia performance of existing materials and envelops was introduced.

2. Evaluating the thermal inertia performance of building envelopes

Building envelops link outdoor environment and indoor environment. Generally, the outer surface of building envelopes gains/losses heat from/to the outdoor thermal environment through two main mechanisms, namely, heat radiation and heat convection. The direction of heat transfer (whether gain or loss heat) depends on the temperature of the outer surface of envelops, the outdoor dry-bulb temperature, the surface temperature of surroundings and solar radiation. When the outer surface of envelops gains/losses heat, its temperature will increase/decrease. The heat transfer between indoors and outdoors is mainly driven by heat conduction, depending on the surface temperatures of inner and outer surfaces. When the temperature of outer surface is higher than the inner surface's, heat is transferred into the building so the indoor environment gains heat from outdoors, and vice versa. According to these basic heat transfer theories, in order to evaluate the thermal inertia performance of building envelops, an indicator is needed which can evaluate the materials' ability of both resisting heat transfer between indoors and outdoors and storing excessive heat either gained from outdoors or generated from indoors.

2.1. Thermal inertia index

Thermal inertia index is an indicator that is used to evaluate the ability of both resisting heat transfer through the building envelops and storing excessive heat either gained from outdoors or generated from indoors. It is defined as the product of the thermal resistance and the heat storage coefficient of materials. The thermal inertia index of laminated composite envelops with PCM is determined as the numerical sum of thermal inertia index of each material layer, as defined in Eq. (1).

$$D_{sum} = \sum D_i = \sum TSC_i \times R_i \tag{1}$$

2.2. Thermal resistance

Thermal resistance is a parameter evaluating the ability of envelops resisting heat transfer. It is dependent on the material's thickness and thermal conductivity. The thermal conductivity of PCM changes insignificantly during the phase change process due to microencapsulation [31], so it can be considered as a constant. The same as thermal inertia index, the thermal resistance of laminated composite envelops with PCM is a numerical sum of thermal resistance of each material layer, which is calculated using Eq. (2).

$$R_{sum} = \sum R_i = \sum \frac{\delta_i}{k_i} \tag{2}$$