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Simulation study on dynamic heat transfer performance of PCM-filled glass window with different thermophysical parameters of phase change material

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ABSTRACT

In order to determine the effects of phase change material's (PCM) thermophysical parameters on the dynamic heat transfer progress of PCM-filled glass window (PCMW), both the numerical model and experimental setup were established. The experimental measurements in typical sunny and rainy summer days with different windows were conducted. Results indicated that when PCM (paraffin MG29) was used in PCMW, the thermal insulation of PCMW and peak cooling load shifting effects were remarkable in the hot summer and cold winter area of China, and the heat entered the building through the PCMW reduced by 18.3% in the typical sunny summer day. Then the effects of PCM's thermophysical parameters on dynamic heat transfer performance of PCMW were investigated by FLUENT based on experimental measurements. The simulated results concluded that the thermal insulation and load shifting effects of PCMW enhanced with the increasing fusion latent heat of PCM and the optimal melting temperature of PCM applied in PCMW was 25–31 °C. Moreover, minimizaiton of temperature difference between liquid phase and solid phase could improve PCMW thermal performance.

1. Introduction

International Energy Agency indicated that the building energy consumption accounted for 31% of the total primary energy consumption in China in 2007 [1]. In the hot summer and cold winter area of China, energy consumption of the building envelope accounted for 60–80% of the total energy consumption in buildings, and the rate of energy consumption through window in the energy consumption through the building envelope was 30% [2]. So the thermal performance of window played an important role on the building energy conservation.

A series of studies related to the energy conservation in transparent envelope were conducted. The vanadium dioxide thermochromic glass window [3] and the near-infrared electrochromic glass window [4] were studied. The thermochromic and electrochromic glass windows reduced the solar radiation heat gain by changing the solar radiation transmittance of the window; as a result energy consumption of the air conditioning system in summer was decreased while the energy consumption of heating system in winter was increased. The double-glazed window with fluid channel was studied to improve the heat recovery and reduce the heat losses [5,6]. It had a complex structure and a high cost, although it could save energy by 25–34% in different regions in China. In addition, the double-glazed windows with semi-conductor solar cells [7] and low-E film [8,9] were investigated. The high cost, complex structure and unsatisfactory annual energy saving efficiency should be improved, although these windows could reduce the energy consumption to a certain extent. Building envelope filled with phase change material (PCM) can smooth the temperature fluctuations of the internal ambient as the external temperature changes, increase the heat capacity and the thermal inertia of the lightweight building walls and as a result improve the thermal comfort of the indoor environment due to PCM's large energy storage density and approximate stationary temperature when the phase change takes place. The double-glazed window filled with PCM was put forward by researchers. It was proposed originally for cold climate conditions and it was also applicable in warm region according to recent studies [10].

Series of studies about the PCM-filled glass window (PCMW) were conducted. Ismail and Henriquez [11,12] studied the overall coefficient of heat transfer (U), the solar heat gain coefficient (SHGC) and the shading coefficient (SC) of the PCMW by numerical and experimental investigations. Results indicated that the *U*-value of PCMW (6 mm glass + 15 mm PCM layer + 6 mm glass)

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Nomenclature

ρ	density (kg m^{-3})
c	specific heat capacity (kJ kg^{-1} °C^{-1})
λ	thermal conductivity (W m^{-1} °C^{-1})
τ	time (s)
t	temperature (°C)
x	thickness (m)
H	specific enthalpy (kJ kg^{-1})
ΔH	latent heat during the phase change process (kJ kg^{-1})
β	local liquid fraction
Q_L	latent heat of PCM (kJ kg^{-1})
α	composite heat transfer coefficient (W m^{-2} °C^{-1})
I	solar radiation in vertical plane (W m^{-2})
γ	solar absorptance of double-glazed window
φ	temperature time lag (h)
f	temperature decrement factor
q	heat flux (W m^{-2})
σ	solar transmittance of double-glazed window
Q	specific cumulative transferred heat (kJ m^{-2})
η	energy saving rate
Q_C	the cooling capacity provided by the fan coil unit in the testing chamber (W)
Q_H	the power of the electric heater in the testing chamber (W)
Q_F	the power of the fan of the fan coil unit in testing chamber (W)
G	the volume flow rate (m^3 s^{-1})

Subscripts

g	glass
a	air
PCM	phase change material
ref	reference value
p	under constant pressure
i	inside, inlet
o	outside, outlet
s	surface of glass
max	maximum
min	minimum
w	water

decreased from 5.22 W m^{-2} K^{-1} to 3.70 W m^{-2} K^{-1} comparing with the simple glass panel (6 mm glass), and the SHGC decreased from 0.821 to 0.660. The optical properties (the extinction, scattering and absorption coefficients) of the PCMW (RT27) were researched by Gowreesunker [13] by the T-history method and spectrophotometry principles, and it was found that visual transmittance values of 90% and 40% are obtained for the liquid and solid phases under stable conditions, respectively. These researches focused on the thermal and optical properties of the PCMW, but paid little attention to the practical application. The thermal performance of PCMW ($CaCl_2{\cdot}6H_2O$) on the condition of simulative heat source was researched by Luo [14]. More experimental investigation needed to conduct, as the PCMW ($CaCl_2{\cdot}6H_2O$) was applied in the simulative environment not in the actual environment, and it was not comprehensive that the interior surface temperature was taken as the single evaluation index to evaluate the thermal performance of the PCMW. The PCMW (paraffin, RT35) which was applied in a humid subtropical climate area was investigated by Goia [15–17]. The heat transferred through the PCMW was calculated and the thermal comfort of the indoor environment was evaluated, the shading and heat insulation effects of the PCMW were significant in high solar radiation, and the PMV value of the indoor environment with the PCMW was lower than the hollow glass window (HW) in summer in the humid subtropical climate area. The PCMW (sodium sulfate decahydrate) applied in the hot summer and cold winter area of China was investigated by Li [18], it was concluded that the annual energy consumption of the air conditioning system and the heating system because of the heat transferred though the PCMW decreased 40.6% comparing with the HW applied, and the thermal insulation and peak cooling load shifting effects of the PCMW in sunny summer day were remarkable, while the dynamic thermal performance of the PCMW was unsatisfactory in the other representative days because it connot decrease the building energy consumption.

According to the literature review, the PCM-filled glass window was investigated simply to reduce heat gain in summer or to store heat from solar radiation in winter. The performance investigation of PCM filled glass window was rare when it is used in a region with both hot summer and cold winter. Investigation indicated that in the hot summer and cold winter area of China, the dynamic thermal performance of the PCMW (sodium sulfate decahydrate) was unsatisfactory in rainy summer day and the thermal performance of sodium sulfate decahydrate was unstable [18]. To improve the thermal performance of PCMW, this paper presented experimental results on the dynamic heat transfer performances of PCMW (paraffin MG29) in representative sunny and rainy summer days, and then numerical simulation investigation on the effects of PCM thermophysical parameters on dynamic heat transfer performance of PCMW were presented in this paper.

2. Numerical model

2.1. Heat transfer process of the PCMW and HW

The heat transfer process of the PCMW and HW is shown in Fig. 1. The solar radiation reaching the glass surface is divided into three parts. The first part is the radiation reflected by the glass surface, the second part is the radiation absorbed by double-glazed window, and the last part is the radiation transmitted through the PCMW and HW. The heat transfer process with the combination of thermal radiation and convection takes place on the boundary of the exterior and the interior surface, respectively.

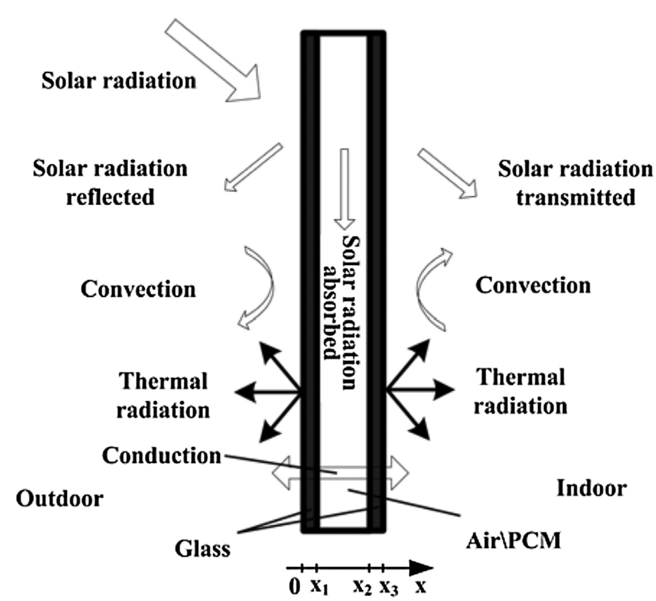

Fig. 1. Heat transfer process of the PCMW and HW.