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Thermal performance of a PCM-filled double glazing unit with different optical properties of phase change material

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ABSTRACT

Phase change material (PCM) applied in the glazing structure can decrease building energy consumption and improve indoor thermal comfort by enhancing its thermal energy storage capacity. In the present work, thermal performance of a PCM-filled double glazing unit with different optical properties of phase change material was investigated numerically. The results show that optical properties of PCM play an important role in the thermal performance of double glazing unit filled with PCM, and effect of PCM phase is also strong. Effect of refractive index of PCM on the temperature of double glazing unit is weak, but the effect of extinction coefficient of PCM on the temperature and transmitted energy of double glazing unit is strong. Compared 200 m^{-1} with 5 m^{-1} of extinction coefficient, time to the highest temperature is 30 and 300 min earlier in liquid and solid PCM of double glazing unit, and time to the highest transmitted energy is delayed 40 min in liquid PCM double glazing unit, but is nearly same in solid PCM double glazing unit.

1. Introduction

Nowadays, energy and environment are two keys in the development of human beings. The energy production from coal and fossil fuel is the preponderant factors for CO_2 emission into the atmosphere, which is widely believed to be contributing to global warming [1,2]. Building is one of the leading sectors of the energy consumption, and especially about 40% of total fossil energy per each year in China was consumed in building sector in the last five years [3,4]. Furthermore, the energy consumption of buildings is still increasing with the developing demand for the life style and the living standards, which will be estimated about 20×10^{12} MJ in 2020 in China [5]. During recent years, developing the novel technology to promote energy efficiency and conservation in buildings has been one of the major issues of governments and societies, whose aim is reducing the energy consumption without affecting the level of thermal comfort in a wide range of weather conditions [6,7].

Glazing units are an indispensable part of a building which provides passive solar gain and air ventilation, for example window system [8]. However, in generally the thermal performance of glazing units are very poor among the building components, and hence they play a significant role in the energy demand of buildings. Their influence on energy loss from building envelope becomes much more drastic when the glazing area is large, for example the heat loss through the glazing envelope accounted for 30% of the energy consumption of the building envelope [9,10]. The thermal performance of a glazing unit is depending on the thermal mass of glazing structure. The effectiveness of thermal mass is based on its ability to absorb and store heat, and dampen the temperature fluctuations within a space. It is widely accepted that thermal mass is beneficial to buildings with respect to increasing thermal comfort and reducing energy consumption [11]. In order to improve thermal mass of glazing units, there are several methods such as optimizing the air layer thickness of double glazing [12], filling the cavity between panes with a participating gas [13], water [14] or aerogel [15], coating pane surface with low emissivity materials [16–18], using multiple pane windows [19–21]. Another alternative practice to enhance thermal mass of glazing units is to increase its thermal storage capacity, which offers improved heat transfer control, results in energy use and energy demand reductions, enhanced occupant comfort, and increased equipment operating life. An effective approach to increase the thermal storage capacity of glazing units is to incorporate phase change material (PCM) in the glazing structure [22–24]. The aim of the PCM-filled glazing unit concept is thus to absorb part of the solar radiation for thermal energy storage, while letting visible radiation enter the indoor environment for daylighting. Therefore, a variety of numerical and experimental work of thermal energy storage solutions for the

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Nomenclature

A_{g1}, A_{p1}, A_{p2}, A_{g2} Solar absorptance of glass 1 layer, phase 1 layer, phase 2 layer and glass 2
$c_{P,g}$, $c_{P,p}$ Specific heat of glass and PCM, J/(kg K)
F_{sky}, F_{ground} View factor between the glazing unit and the sky dome, between the glazing unit and the surrounding surfaces
H, h_{out}, h_{in} Specific enthalpy of PCM, J/kg; convective heat transfer coefficient of the exterior surface of outer glass, inner surface of internal glass, W/(m^2 K)
I_{sol}, $I_{g\to p}$, $I_{p,l\to p,s}$, $I_{p\to g}$ Solar radiation, radiative heat flux of coupled surface between outer glass and PCM, liquid–solid interface in the PCM region, coupled surface between internal glass and PCM, w/m^2
k_g, k_p, $k_{p,l}$, $k_{p,s}$ Thermal conductivity of glass and PCM, liquid PCM near to liquid–solid interface, thermal conductivity of solid PCM near to liquid–solid interface, W/(mK)
L_{g1}, L_{p1}, L_{p2}, L_{g2} Thickness of glass 1 layer, phase 1 layer, phase 2 layer and glass 2, m
n_g, n_{p1}, n_{p2} Refractive index of glass, phase1 and 2 of PCM
$S(t)$, QL Thickness of liquid PCM, m; latent heat of PCM, J/kg
q_{rad}, $q_{rad,air}$, $q_{rad,sky}$, $q_{rad,ground}$ Radiative heat exchange between exterior surface of outer glass with the outdoor environment, with the air, sky and ground of outer glass, w/m^2
T_{g1}, T_{p1}, T_{p2}, T_{g2} Solar transmittance of glass 1 layer, phase 1 layer, phase 2 layer and glass 2
T, T_{ref}, T_s, T_l Temperature, reference temperature, temperature that the phase of PCM starts to change from solid to liquid, PCM completely changed into liquid, K
T_g, T_p, $T_{p,l}$, $T_{p,s}$ Temperature of the coupled surface of outer glass, coupled surface of PCM, liquid PCM near to liquid–solid interface, solid PCM near to liquid–solid interface, K
T_{out}, $T_{a,out}$, T_{sky}, T_{in}, $T_{a,in}$ Temperature of the exterior surface of outer glass, ambient, sky temperature, inner surface of internal glass, indoors air, K

Greek letter
α_g, α_{p1}, α_{p2} Extinction coefficient of glass, phase1 and 2 of PCM, m^{-1}
β Liquid fraction, –; a factor that splits the heat exchange with the sky dome between sky and air radiation
ρ_g, ρ_p Density of glass and PCM, kg/m^3
ρ_1, ρ_2, ρ_3, ρ_4 Interface reflectance for surface between air and glass, for surface between phase 1 of PCM and glass, for surface between phase 1 and phase 2 of PCM, for surface between phase 2 of PCM and glass
τ Time, s
ϕ Radiative source term, W/m^3
ε Surface emissivity of glass
σ Stefan–Boltzmann constant
θ Angle between the glazing unit and the ground

Subscript
a Air
con Convective
g, p Glass and PCM
in, out Inner surface and exterior surface
rad Radiative
sol Solar radiation intensity
l, s Liquid and solid PCM

integration of PCM into glazing unit have been developed, which have been attracted more and more attention as a potential technology for minimizing energy consumption in the buildings [25–35].

Ismail et al. [25] experimentally investigated optical and energy performance of glass windows filled with air and PCM in the wavelength range of 300–2800 nm by using Perkin-Elmer Lambda, and they found that the transmittance and reflectance of glass windows filled with PCM have large reductions in the infrared and ultraviolet radiations while maintaining good visibility compared with filling air, and the reduction of the transmitted energy of glass windows filled with PCM is of the order of 50%. They noticed that the increase in the thickness of the PCM layer has a marginal effect on the energy transmitted from the optical view point, although the thermal effect is very noticeable. Ismail et al. [26] also developed one dimensional radiation and heat conduction model of double glass window filled with PCM, and numerically found that the solar heat gain coefficient of double glass window filled with PCM is in the range of 0.65–0.80, when the external and internal ambient temperatures are respectively 35 and 24 °C, and the incident solar radiation is 600 W/m^2, however the authors did not state the detailed optical and thermal parameters of PCM.

Li et al. [27] proposed two optical parameters to calculate the solar absorptance and transmittance of the glass window filled phase change material (PCMW), and investigated the energy performance of PCMW in the hot summer and cold winter area of China. The authors concluded that in the representative sunny summer day, the peak temperature on the interior surface of the PCMW reduced by 10.2 °C, and the heat entered the building through the PCMW reduced by 39.5%, comparing with the hollow window, when the solar absorptance and transmittance of the PCMW is at constants 0.19 and 0.76. Zhong et al. [28] investigated the effects of thermophysical parameters of PCM on the dynamic heat transfer of PCMW, and indicated 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, minimization of temperature difference between liquid phase and solid phase could improve PCMW thermal performance. Goia et al. [29] introduced optical properties of PCM in solid and liquid phase state to a numerical model, which describes the thermo-physical behaviour of a PCM layer in combination with other transparent materials to perform numerical analyses on various PCM glazing systems configurations, and found that a good agreement between simulations and experimental data is achieved.

Goia et al. [30–33] and Gowreesunker et al. [34] contributed a lot to the fundamental aspect of energy and optical properties of PCM glazing units. For example, Goia et al. [30,31] measured the spectral and angular behaviour of different PCM glazing samples that are characterized by different thicknesses of PCM by commercial spectrophotometer and a dedicated optical test bed, and found that when the PCM is in liquid state and in solid state, the relevant difference in the spectral feature of PCM can be seen. When the PCM is in the solid state, the reflectivity of the system is far higher (up to three times) than when it is in the liquid state. The absorption coefficient of the solid PCM is much higher than that of the liquid PCM. The thickness of the PCM layer has a high impact on the absorption coefficient and transmittance, but which has a weak effect on the reflectivity. Goia et al. [32,33] proposed a full-scale prototype of a PCM glazing system and analyzed its energy performance. And they found that the experimental results have highlighted a good ability of the PCM glazing to store solar energy and to smooth and delay peak values of the total heat flux. Gowreesunker et al. [34] investigated the thermal and optical performance of a PCM-glazed unit using the T-history method and spectrophotometry principles, and they found that (i) during rapid phase changes,