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Research on heat transfer performance of passive solar collector-storage wall system with phase change materials

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ABSTRACT

Heat transfer performance on the wall has a great influence on energy conservation and indoor thermal comfort. In this paper, a new type of passive solar energy utilization technology, phase change materials (PCMs) added into passive solar collector-storage wall system was proposed. Heat transfer performance and energy saving characteristics were investigated theoretically and experimentally. Energy balance equations that including sunlight board, air in the channel, collector mortar layer and inner surface of wall were established to describe the heat transfer process of system. Experimental room was used to studied the energy saving characteristics in winter. The results indicate that the new passive solar collector-storage wall system with PCMs can promote indoor air thermal circulation and decrease indoor air temperature fluctuations. Its good heat storage capacity can apparently improve indoor thermal environment. Therefore, this new passive solar collector-storage wall system with PCMs can be popularized in engineering applications.

1. Introduction

Passive solar collector-storage wall system is widely used in engineering applications [1–4]. It consists of a glazing wall, an air channel, a massive wall and an insulating wall. In winter, solar radiation is absorbed and stored in massive wall when bottom and top vents opened at daytime, the heated air in channel flow into room to improve indoor temperature. At night, the energy that stored in wall is released into the room when all vents closed. In summer, by opening bottom vent of massive wall and top vent of glazing wall, air in channel rises to outdoor under heat pressure, ventilation and cooling take place [5].

Numerous studies have been focused on the heat transfer performance of passive solar collector-storage wall system. Khalifa and Abbas [6] simulated the heat transfer characteristics of the thermal storage wall. Chel et al. [7] estimated the passive heating potential of Trombe wall for a honey storage building by TRNSYS. The thermal storage wall can enhance the availability of the solar energy, but the outside surface temperature of external wall rises slowly in winter with a long lag time. Chen and Liu [8] analyzed the variation of flow and temperature field in the composite solar wall and the effects of the particle size, the porous within porous layer, the material and the position of porous absorber on heating, the result show that all factors should be taken into account for a better design of the heating system. Zhang et al. [9] investigated the heat transfer performance and energy-saving characteristic of wall implanted with heat pipes, the result shows that the new system can apparently reduce the heating load and improve thermal environment.

However, passive solar collector-storage wall system cannot both meet heating in winter and ventilated/cooling in summer. To solve this problem, phase change materials (PCMs) are used in building envelope. Phase change materials can not only decrease the building energy consumption, but also improve the indoor thermal comfort by enhancing thermal energy storage capacity [10–14]. The application of PCMs has been focused on brick, concrete, mortar and other wall-covering materials. Principi and Frioretti [15] discussed the possibility of increasing energy performance of thermal brick through integration with PCM. Zalewski et al. [16] presents an experimental study of a small-scale Trombe composite solar wall. PCM was inserted into the wall in the form of a brick-shaped package and energy performance of wall from heat flux measurement and enthalpy balances also presented. Haurie et al. [17] studied the effect of different flame retardants on the fire behavior and mechanical properties of epoxy mortars. The results prove the effectiveness of the tested flame retardants on the improvement of the fire properties of the epoxy mortars without a significant decrease on their mechanical properties. Kong et al. [18] established a mathematical model of two new PCM systems combined

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Nomenclature

α_1	Transmissivity of sunlight board
α	Absorptivity of sunlight board to sun
β	Absorptivity of collect mortar layer to sun
δ_a	Channel thickness (m)
δ_i	Each layer thickness of wall (m)
δ_w	Collector mortar layer thickness (m)
δ'_w	Inner surface of wall thickness (m)
ε_s	Emissivity of sunlight board
ε_w	Emissivity of collector mortar layer
λ_i	Each layer thermal conductivity of wall materials (W/mK)
γ	Mass percentages of PCM in collect mortar layer (%)
γ'	Mass percentages of PCM in wall (%)
λ	Specific heat of mortar (J/kgK)
$c_{p,s}$, $c_{p,m}$, $c_{p,l}$	Specific heat of PCM in process of solid, solid-liquid, liquid (J/kgK)
m	Mass flow rate of air in channel (kg)
m_m	Mass of collect mortar layer(kg)
$m_{m'}$	Mass of inner surface mortar layer (kg)
ρ	Density of air (kg/m^3)
ν	Wind velocity (m/s)
h_{so}	Convective heat transfer coefficient between sunlight board and outside air (W/m^2K)
h_{sa}	Convective heat transfer coefficient between sunlight board and air in channel (W/m^2K)($h_{as} = h_{sa}$)
h_{wa}	Convective heat transfer coefficient between collector mortar layer and air in channel (W/m^2K)($h_{wa} = h_{aw}$)
h_{sw}	Radiative heat transfer coefficient between sunlight board and collector mortar layer () ($h_{ws} = h_{sw}$)
A_s	Sunlight board area (m^2)
A_w	Outer surface area of collector mortar layer (m^2)
$A_{w'}$	Inner surface area of wall (m^2)
D_h	Hydraulic diameter of flow interlayer (m)
H	Channel width (m)
I_c	Solar radiation intensity (W/m^2)
T_a	Air temperature in channel (K)
T_{in}	Indoor temperature (K)
T_{out}	Ambient temperature (K)
T_t	Top vent temperature (K)
T_b	Bottom vent temperature (K)
T_s	Sunlight board surface temperature (K)
T_n	Inner surface temperature of collect mortar layer (K)
$T_{n'}$	Inner surface temperature of wall (K)
T_w	Outer surface temperature of collect mortar layer (K)
$T_{w'}$	Outer surface temperature of wall (K)
T_1	Phase change temperature of PCM in collect mortar layer (K)
T_2	Phase change temperature of PCM in wall (K)
R_e	Reynolds
P_r	Prandtl number

in the building envelope and studied their thermal performance. It is found that the numerical simulation achieved good validity. Ling et al. [19] studied the active heat storage performance of the active-passive triple phase change material wall and solar concentrators. This new system can improve the heat storage capacity.

In the present study, we have explored a new system: passive solar collector-storage wall contained PCMs on both sides surface. The heat transfer performance and energy saving characteristics were investigated theoretically and experimentally.

2. Description of new wall system

Passive solar collector-storage wall system with PCMs locates on the south side of room. From outside to inside, the system is made up of a 6-mm-thick sunlight board, a 15-mm-thick collector mortar layer, a 40-mm-thick extruded board, a 390 mm × 190 mm × 190 mm concrete block and a 15-mm-thick phase change mortar layer. The air gap between sunlight board and collector mortar layer is 100 mm. Four vents with dimension of 200 mm × 200 mm are located at the top and bottom position of wall. Paraffin/expanded perlite/graphite PCMs that prepared in our previous word [20] are added into collector mortar layer and interior mortar layer to storage energy. Phase change temperature and latent heat are 19.45 °C and 128.46 J/g, respectively. The illustration of passive solar collector-storage wall system with PCMs is shown in Fig. 1. A part of solar energy transmits into the room through air channel and vents to improve indoor temperature, a part of solar energy store in the collector mortar layer through PCMs and the rest solar energy is conducted slowly through massive wall to the room by radiation and convection.

The advantage of passive solar collector-storage wall system with PCMs is storing more heat from sun during the day and releasing it into the building during the night.

3. Theoretical analysis

The heat transfer process of passive solar collector-storage wall system with PCMs is very complex. In order to investigate the process theoretically, the following assumptions have been made while establishing equations:

(1) Long wave radiation is negligible.
(2) The effect of thermal capacity and thickness of sunlight board is negligible.
(3) Sunlight board is considered to be opaque for infrared radiation.
(4) Reflections of sunlight board and collector mortar layer are assumed to be neglected.

Heat transfer process of passive solar collector-storage wall system with PCMs is expressed by energy balance equations including sunlight board, air in the channel, collector mortar layer and inner surface of wall.

3.1. Sunlight board energy balance equation

Energy balance suggests that the amount of energy must be equal to the useful energy gain at a given time. Therefore, sunlight board energy balance equation can be written as: solar radiation by sunlight board from sun + radiation heat between sunlight board and outer surface of collector mortar layer = convective heat between sunlight board and outdoor ambience + convective heat between sunlight board and air in the channel:

$$\alpha I_c(\tau)A_s = h_{sw}A_w\left[T_s(\tau) - T_w(\tau)\right] + h_{so}A_s\left[T_s(\tau) - T_{out}(\tau)\right] + h_{sa}A_s\left[T_s(\tau) - T_a(\tau)\right] \quad (1)$$

where the radiation heat transfer coefficient between sunlight board and outer surface of collector mortar layer h_{sw} is given below [21]

$$h_{sw} = \frac{\sigma\left[T_s^2(\tau) + T_w^2(\tau)\right]\left[T_s(\tau) + T_w(\tau)\right]}{\left(\frac{1}{\varepsilon_s} + \frac{1}{\varepsilon_w} - 1\right)} \quad (2)$$

The convective heat transfer coefficient between sunlight board and outdoor ambience h_{so} is given by [22], includes convection