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Experimental investigations on the performance of a collector–storage wall system using phase change materials

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ABSTRACT

Experiments have been performed on the thermal behavior of a collector–storage wall system using PCM (phase change material). PCM slabs were attached on the gap-side wall surface to increase the heat storage. The test was carried out for a whole day with charging period of 6.5 h and discharging period of 17.5 h, respectively. Wall and air temperatures as well as air velocity in the gap were measured for analysis. The results showed that the PCM surface temperature increases first rapidly, then slowly and rapidly again during the charging process, which in turn corresponds with the three storage stages: sensible heat (solid), latent heat (melting) and sensible heat (liquid), respectively; while in the discharging process the PCM surface temperature decreases slightly shortly after the initial sharp drops, which suggests the long time period of solidification for PCM to release latent heat. Subject to the variations of PCM surface temperatures, similar trends were also found for the gap air temperatures, glazing temperature and indoor temperature. Both the air flow rate and heating rate by air circulation have up and down fluctuations during the charging period, and then, shortly after initial sharp drops, they keep at nearly steady values during the discharging period. The indoor temperature was found to be above 22 °C during the whole discharging period (17.5 h) under present conditions, which indicates that the indoor thermal comfort could be kept for a long time by using PCM in collector–storage wall system.

1. Introduction

A traditional collector–storage wall (also called Trombe wall) usually consists of a glazing, a massive wall and the air channel/-gap formed between the glazing and the wall with upper and lower vents connecting with the room. Solar rays penetrate the glazing and are absorbed and stored as thermal energy by the massive wall with prominent temperature changes [1,2]. Part of the heat energy is then transferred from the wall to the room by conduction, and is also exchanged to the air in the channel/gap by convection and then is ejected into the room through the upper vent driven by buoyancy [3,4]. Many experimental and numerical studies have been performed on massive Trombe wall systems and it was found that the thermal performances of the Trombe wall depend on various parameters such as the size of air gap and vents [5,6], wall area and orientation [7–9], wall thickness [10,11], glazing [12–15], insulation [7,13,15] and operation strategy [7,16]. Recently, PCM (phase change material) application in buildings has been recently attracting wide attentions due to the high thermal storage intensity and narrow temperature change during phase transitions [17–19]. PCMs could be incorporated into building walls [20–22] and roof [23] to increase the thermal mass of these building envelopes and then improve the indoor comfort. PCMs could also be included in the collector– storage wall by attaching PCM plates onto the wall or incorporating PCM into the wall materials, which improve the thermal mass, decrease the wall thickness and save space [24]. Several researchers have investigated the performance of PCM collector– storage wall system. Telkes [25] set up the earlier PCM Trombe wall using Glaubert salt for thermal storage installed behind a polyhedral glazing but no thermal performance was reported. Experimental study by Benard et al. [26] showed that controlled air circulation would give much better results; their followed work [27] indicated that the advantage of the paraffin walls over the concrete is a mass reduction and controlled front heat extraction should considerably improve the thermal performance. Knowles [28] did a numerical work and found that paraffin–metal wall could reduce the storage mass and increase the efficiency. Ghoneim et al. [29] applied one dimensional thermal circuit network model to simulate the PCM collector– storage wall and pointed out that lower melting

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Nomenclature

A	area (m^2)
A_c	cross sectional area of air gap (m^2)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
h	hour
H	vertical height or spacing (m)
H_m	heat of fusion of PCM (kJ/kg)
k	confidence factor
k_c	coverage factor
L	vertical length (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
M	mass of the PCM slabs (kg)
n	number of PCM slabs
P	electric power of dysprosium lamp (W)
PCM	phase change material
PVC	polyvinyl chloride
Q	energy (kJ)
$\dot{Q}_h$	heating rate by air circulation (W)
q	energy flux ($W\,m^{-2}$)
S	horizontal distance between lamp and glazing (m)
t	temperature (°C)
t_m	melting temperature of PCM (°C)
t_e	environment temperature (°C)
t_{end}	PCM temperature at the end of charging process (°C)
U	average velocity ($m\,s^{-1}$)
V	volume (m^3)
wt	weight

Greek Letters

δ	thickness (mm)
α	absorptivity
ρ	density ($kg\,m^{-3}$)
η	efficiency
τ	time period (h)
γ	transmissivity of glazing

Subscripts

a	air
c	cross section or coverage factor
ch	channel
e	environment
E	expanded
g	glazing
in	inlet
is	insulation
l	liquid
lc	light channel
m	mean or melting point
out	outlet
r	room
s	solid
w	wall

temperature of PCM (paraffin) provided larger solar saving fraction due to the lower heat loss.

Stritih and Novak [30,31] used a transparent insulating material (TIM) to prevent heat loss into the surroundings. Manz et al. [32] also investigated the performance of TIM–PCM collector–storage wall using $CaCl_2{\cdot}6H_2O$ (t_m = 26.5 °C) for heat storage and parameter studies indicated that a decrease of the mean melting temperature to approximately 21 °C could be advantageous.

Onishi et al. [33] performed an unsteady simulation of the collector–storage wall system with 25 wt% inorganic PCM in concrete wall in Japan using a CFD code and their results indicated the effectiveness of PCM for developing low energy houses with the introduced hybrid system. Khalifa and Abbas [34] numerically examined the thermal performance of collector–storage wall using different storage materials, namely concrete, $CaCl_2{\cdot}6H_2O$ and Paraffin and concluded that the 8 cm-thick storage wall of hydrated salt could maintain the room comfortable with the least temperature fluctuation. Fiorito [35] selected five cities of different climate zones in Australia and modeled the effect of PCMs (n-paraffin and wax) integrated in collector–storage walls. The simulation results showed that PCM improved the thermal inertia of lightweight constructions and its position and melting temperature need to be optimized according to the corresponding climate conditions. Kara and Kurnuc [36] applied novel triple glazing for PCM wall (33 wt% paraffin granules in the plasterboard) to prevent overheating in summer and their experimental results indicated that the wall including PCM (GR35) with relatively lower melting temperature t_m = 34 °C presents better performance than that including PCM (GR41) with t_m = 45 °C while both could provide 14% of annual heat load of the test room.

Zalewski et al. [37] performed an experimental study of a small-scale composite solar wall where PCM was inserted into the wall in the form of brick-shaped package. The PCM used is a mixture of hydrated salts (water + $CaCl_2$ + KCl + additives) with melting point of 27 °C. They concluded that the solar gains are released with a time lag which indicates the advantage of this composite solar wall. They also pointed out that the efficiency of the solar wall could be improved by limiting losses to the outside and increasing exchanges in the cavity. Li and Liu [38] experimentally investigated the thermal performance of a PCM (paraffin, t_m = 41 °C) based solar chimney under three different heat fluxes on the absorber surface and found that 700 W m^{-2} of heat flux drives the highest air flow rate (0.04 kg/s) while 500 W m^{-2} generates the highest average outlet temperature (20.5 °C). They also reported that phase change periods are nearly 13 h 50 min for all cases investigated.

The above experimental and simulation works on PCM collector–storage wall were summarized in Table 1. It is indicated that there are few experimental works done on detailed kinetic and thermal behavior of a collector–storage wall system where PCM was included for heat storage. Particularly, the transient variations of air flow rate, heating rate and system temperatures (temperatures of PCM, wall, air in channel and in the room) during charging and discharging processes are still unclear for a PCM collector–storage wall. Also, insulation measures are needed at night to reduce the heat losses to the outside environment, which are quite important for better thermal performance of Trombe wall system [39,40]. Therefore, the aim of the present paper is to set up a PCM collector–storage wall system with an insulating curtain mounted between the glazing and the wall, which is unwrapped during the discharging process to reduce the heat losses to the environment. Detailed measurements on transient temperature profile in the wall system, air flow rate in gap and heating rate to the indoor room will be performed during charging and discharging processes to test its performances. The obtained results will provide references for the design of PCM collector–storage wall system for passive solar heating and could also be used for validation of simulation studies.