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The thermal behavior of Trombe wall system with venetian blind: An experimental and numerical study

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ABSTRACT

The increasing interest in studying a Trombe wall with venetian blind (VBTW) has heightened the need for computational tools suitable to predict its thermal behavior. In this paper, a dynamic numerical model of a building with a VBTW was developed. Experiment has been conducted to study the temperature field of the whole building system in cold weather. It was found that the simulation results were in good agreement with the experimental data. The comparisons between the room with the classic Trombe wall and that with the VBTW were made based on the proposed model. The results demonstrated: the optimum time to open air vents of the VBTW was approximately 1.5 h earlier than that of the classic Trombe wall after sunrise; the air average temperature for room with the VBTW was about 5.5 °C higher compared to that with the classic Trombe wall in the daytime; the heat loss of the VBTW was smaller at night. The average predicted mean vote for the three rooms (room with the VBTW, room with the classic Trombe wall and room without Trombe wall) were −1.0, −1.5 and −2.2 in the daytime respectively. In conclusion, a building integrated with the VBTW can not only reduce heating energy needs but also achieve an acceptable condition of comfort in cold weather.

1. Introduction

Nowadays due to the heating, ventilating and air conditioning (HVAC), building energy consumption is growing. It is essential to make greater use of the renewable energy, e.g. solar energy, to provide space heating energy for building. Trombe wall, which is also known as storage wall and solar heating wall (SHW) [1,2], is regarded as a feasible and sustainable technology of the solar utilization in building due to its simple configuration, high efficiency and zero running cost. It is made up of a south-facing masonry wall with high thermal inertia and black color, an air gap and an outside glazing. The masonry wall is equipped with two vents at the top and the bottom for the air thermo-circulation between the air gap and indoor space. The earlier research demonstrated that it could reduce a building's energy consumption up to 30% [3]. Several researches on theory and experiment have been conducted for Trombe wall.

Khedari et al. [3] studied the commercial modified Trombe wall (MTW) and the results showed that the MTW could induce natural ventilation well. Chen et al. [4] carried out an experiment on the heat preservation effect of the shading device on a winter night. Burek et al. [5] conducted an experiment of heat transfer and mass flow in Trombe wall and they concluded that the mass flow rate through the channel was a function of both the heat input and the channel depth. Yilmaz et al. [6] conducted a comparative experiment of Trombe wall systems with single glass, double glass and PV panels in Turkey and validated the experimental results with CFD. Chen et al. [7] clarified the effect of humidity adjustment of Trombe wall on indoor environment by the experimental and theoretical analysis based on steady moisture transfer theory. Shen et al. [8] developed the models of composite Trombe solar walls with the finite differences method (FDM) and TRNSYS software. The calculation presented that the composite wall has better energetic performances than the classic Trombe wall in cold and/or cloudy weather. To simulate the air flow of the room with Trombe wall, Hamia et al. [1] proposed a 2D dynamic model with the Computational Fluid Dynamics (CFD). They obtained the temperature and air flow rate on the level of the zone of occupation. Stazi et al. [9] made comparisons between Trombe wall systems and conventional wall systems all year round. The results demonstrated that Trombe wall system could provide heating energy savings and thermal comfort in winter and intermediate seasons. Trombe wall with PV cells (PVTW) was studied by scholars [10–14]. A novel Trombe wall with venetian blind (VBTW) was proposed in our previous work. The venetian blind was covered with selective absorbing coatings. Its angle could be adjusted as required, which ranged from −90° (the

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Nomenclature

A	area (m^2)
c	specific heat capacity (J/(kg K))
D	width of the Trombe wall (m)
h	coefficient of heat transfer (W/m^2 K; sun height angle (°)
λ	thermal conductivity (W/(m K))
H	height (m)
I	global solar radiation (W/m^2)
L	depth (m)
m	mass (kg)
N	number
Nu	Nusslet number
P	permeability
q	volume flow rate (m^3/s)
Ra	Rayleigh number
s	temperature gradient (°C/m)
T	temperature (°C)
t	time (s)
V	air flow velocity (m/s)
W	the external work (w)

Greek

α	absorptivity; thermal diffusivity (m^2/s)
Φ	solar radiation absorbed by the layer (W)
β	factor of expansion (K^{-1})
δ	the difference (m)
ε	emissivity
τ	transmissivity
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($W/(m^2 K^4)$)

Subscripts

a	air
c	convection heat transfer
cl	clothes
ca	air in the cavity
$L1$	glass
$L2$	venetian blind
$L3$	masonry wall
i	interior surface
f	friction factor
r	room
rad	radiation heat transfer
in	air inlet
out	air outlet

side was covered with high reflectivity coating) to 90° (the side was covered with high absorptivity coating) from the horizon, as shown in Figs. 1 and 3. We have studied the component of venetian blind with a three-dimensional steady CFD model [15]. The results showed that the position of venetian blind, the width of the air gap and the area of the air vents influenced the thermal efficiency of the VBTW.

The purpose of this paper aimed to study the thermal behavior of a building with VBTW. We proposed a dynamical numerical model to simulate all of the building's components. Experiment has been conducted to investigate the temperature field of the whole building system. The numerical results were validated with the experimental data. Then, with the proposed model we compared the thermal characteristic between room with the VBTW and that with classic Trombe wall on several aspects: the optimum time to open air vents after sunrise, the indoor air temperature and air temperature rise rate, the heat loss at night, predicted mean vote (PMV) value and the local thermal discomfort.

2. Experimental setup

2.1. Test cells description

The experimental platform is located at the Laboratory of University of Science and Technology of China, Hefei. As shown in Fig. 2, the test platform consists of two rooms with the dimensions of width 3800 mm/depth 3900 mm/height 2600 mm. Except for the south wall of the test room, the other components of the rooms are constructed identically. Two Trombe walls with venetian blind are applied on the south façade of test room, and the size of each VBTW is: height 2 m/width 1 m. Fig. 3 shows the structure of VBTW. The outer pane, $L1$, is 5 mm thick, which can be open to adjust the angle of venetian blind manually. The masonry wall, $L3$, is 0.24 m thick solid concrete brick. The air gap between $L1$ and $L3$ is 0.14 m deep. Venetian blind, $L2$, are installed in the middle of the air gap. For convective heat transfer, two vents are located at the upper and the lower positions of the masonry wall, each one measuring 0.4 m/0.12 m (Fig. 3).

2.2. Test procedure and instruments

The experimental data reported in this paper refer to the period from16th January to18th January 2015. During the whole test procedure, venetian blind was inclined at the angle of 60° (from the horizon) from the time of opening air vents to the time of closing air vents, while it was adjusted to the angle of −90° (characterized by the low emissivity, see Fig. 1) except the time range. Table 1 shows the operation time of air vents. Testing parameters include the temperature, global solar radiation intensity of the south elevation and the angle of 60° from the horizon, which are measured by thermocouple thermometers (copper-constantan, ±0.5 °C) and solar pyranometer (TBQ-2, ±11.104 μv/W m^{-2} and ±11.601 μv/W m^{-2}), respectively. Fig. 3 shows the test positions.

3. Mathematical model and simulation

In this study, a dynamic model for the building with VBTW is developed. By considering the absorbed solar radiation, long wave radiation exchange between layers, convective heat transfer between the cavity air and the layers, heat conduction in the wall, and flow and heat transfer of the indoor air, the model comprises three coupled parts: Trombe wall with venetian blind (VBTW) model, the building envelops model, and indoor air model. VBTW model include three components: the outside glazing ($L1$), the air in the gap (ca) and the venetian blind ($L2$). To develop the model for the whole system, the following assumptions are established:

(1) The material properties are independent of temperature in this study, such as specific heat capacity and thermal conductivity.
(2) Because the transmissivity of the glass and the absorptivity of venetian blind are very high, the radiation reflected from them are negligible.

Table 1
The operation time of air vents and weather condition.

Date	Weather condition	Operation time of two vents	
		Open	Close
Jan. 16th, 2015	Sunny	10:00	16:51
Jan. 17th, 2015	Sunny	9:14	16:59
Jan. 18th, 2015	Cloudy and sunny	9:27	16:45