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Thermal behaviour of Trombe wall with venetian blind in summer and transition seasons

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Abstract

Trombe wall with venetian blind can work in winter heating mode, summer sunshading mode and transition season ventilating mode. In this study, the thermal performance of the Trombe wall with venetian blind in summer and transition seasons is analyzed using the computational fluid dynamics (CFD) modeling. A 2-D model was developed and validated using experimental data. The model was employed to determine the induced air flow and heat transfer of Trombe wall in summer and transition season mode. The effects of the system configuration on the thermal performance were investigated. The results show that larger spacing between the slat and inner wall and larger slat angle help enhance the natural convective flow and reduce the air temperature in both summer and transition seasons, thus leading to better cooling effect and less solar radiative heat gain of the external wall. The natural convective flow rate is more sensitive to the area of the outlet vent than that of the inlet vent.

Keywords: Trombe wall; Venetian blind; Solar utilization; Natural ventilation; Energy saving

1. 1. Introduction

It is well known that the building sector is a major energy consumer in urban cities. According to the previous study, buildings consumes 1/4-1/3 of the total energy supply, mainly due to the heating, ventilating and air

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conditioning (HVAC) demand[1]. Making good use of renewable energy and natural ventilation is a promising approach to increase the energy efficiency in buildings.

Nomenclature

A	effective absorbing area (m^2)
C_p	specific heat capacity (J/kg-K)
G	solar radiation intensity (W/m^2)
h	convective heat transfer coefficient (W/m-K)
m	air mass flow rate (kg/s)
Q	energy rate (W)
T	temperature (K)
RE	relative error
V	wind speed (m/s)
X	value
Subscripts	
exp	experimental
th	radius of
in	inlet
out	outlet
sim	simulated

A passive solar thermal facade such as the Trombe wall is a building wall that has incorporated a glass panel and a ventilated air space into its structure. Many researchers proposed different improvement schemes, such as using phase change materials [2], fluidized particles [3] and water [4] as thermal storage materials, and studied their impacts on the thermal performance of the Trombe wall. Imessad et al.[5] introduced the Barra-Costantini wall that used metal plate as the heat absorber. Ji Jie et al.[6] proposed PV-Trombe wall with photovoltaic cells on the glazing, which could produce electricity and heat simultaneously. However, the above strategies still encountered wall overheating problem during summer operation. In order to reduce the summer cooling load of Trombe wall utilization, several improvements have been proposed. A Z-Trombe wall was proposed by the National Renewable Energy Laboratory(NREL) [7]. Spain Sofia Melero et al. [8] proposed a composite porous ceramic evaporative cooling Trombe wall to achieve winter heating and summer evaporative cooling.

In the past, we developed a Trombe wall with venetian blind structure in order to realize the active control of the heating and passive cooling [9], as shown in Fig. 1. By applying a venetian blind structure, the absorbed irradiance can be controlled by adjusting the slat angle. Trombe wall can work under the winter air heating mode, transition season ventilating mode or summer sunshade mode. In previous research, several works have focused on modelling and analyzing the solar thermal performance the Trombe wall with venetian blind in winter [9]. However, the thermal performance in summer and transition seasons, which is an important function of the Trombe wall with venetian blind, is still not well understood. Therefore, the aim of the present work is to analyse the thermal performance of the Trombe wall with venetian blind structure in summer and transition season mode.

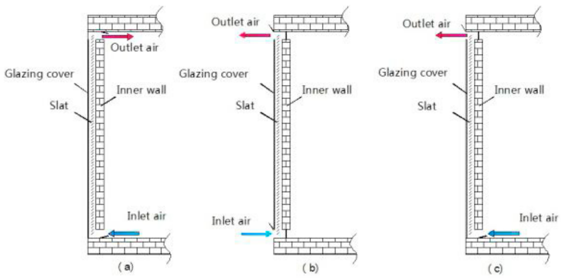

Fig. 1: Schematics of Trombe wall with venetian blind structure: (a) winter mode; (b) summer mode; (c) transition season mode.

2. 2. CFD model

In this study, the CFD approach is used to simulate the velocity and temperature profiles in the computational domain. The commercial CFD tool FLUENT is chosen as the software platform in this study. Based on a grid independence study, the computational grid numbers of 1.2 million and 1.08 million are used in the simulations of transition season model and summer model, respectively.

The boundary conditions need to be set correctly in order to obtain accurate and realistic results. The inlet, ambient and the wall boundary conditions are specified using the measured data. The gravitational acceleration is imposed on the air, and the inlet and outlet air vents are set as pressure outlet boundaries with the measured temperature as backflow conditions. The air thermo-physics properties are considered to be constant except for the density, using Boussinesq approximation to investigate the buoyancy effect.

All surfaces boundary conditions are assumed to be no slip velocity boundary conditions. The glass panel is set as convective wall boundary. The convective heat transfer coefficient of the glass panel is given by [10]

$$h = 5.7 + 3.8V \tag{1}$$

where V is the wind speed in m/s. When the solar radiation strikes on the venetian blinds through the glass panel, most of it is absorbed and the heat is transferred to the air in the cavity. The blinds are set as the heat flux wall boundaries, which absorb solar radiation. Other walls are assumed to be adiabatic boundary conditions.

The solar thermal efficiency of the Trombe wall with venetian blind is defined as the ratio of the heat absorbed by the air in the cavity to the overall solar energy strikes on the south wall, given by [10]

$$\eta = Q_{th} / (\mathrm{Qg A}) \tag{2}$$

where A is the effective absorbing area of 1.7m^2; G is the vertical solar radiation; Q_{th} is the heat absorbed by the air in the cavity, kJ, which can be calculated as follows [10],

$$Q_{th} = \mathrm{mg C}_p (T_{out} - \mathrm{T}_{in}) \tag{3}$$

The CFD simulation evaluates the steady-state operation using pressure based implicit solver. The turbulence model selected in this study is KOM model. The radiation heat transfer is determined using S2S radiation model. PRESTO! scheme is used for interpolation of pressure. SIMPLE algorithm is used for Pressure-Velocity Coupling. The second order upwind scheme is applied for solving the transport equations. The convergence criterion is set up by applying residuals of the order of 10^{-6} for energy and of the order of 10^{-4} for other quantities.

3. Model validation

Model validation was conducted by comparisons between the modelling results and experimental measurements. In the previous study [9], experiments were conducted to measure the temperature distribution and natural convective flow rates of Trombe wall with venetian blinds. The test conditions of the experiments can be found in [9]. The root mean square percentage deviation (RE) is used and it can be calculated by:

$$RE = \sqrt{\frac{\sum [100 \times \left(X_{\exp} - X_{sim} \right) / X_{\exp}]^2}{n}} \tag{4}$$

Figures 2 provides comparison between the CFD simulations and the experimental data for the outlet air temperature, solar thermal efficiency and air mass flow rate. In general, a good agreement is obtained for each set of comparison. The RE values of the outlet air temperature, solar thermal efficiency and air mass flow rate are 0.3%, 3.2% and 5.6% respectively. The results show that the model setup and assumptions made can generate reliable simulations for the present thermal analyses of Trombe wall.

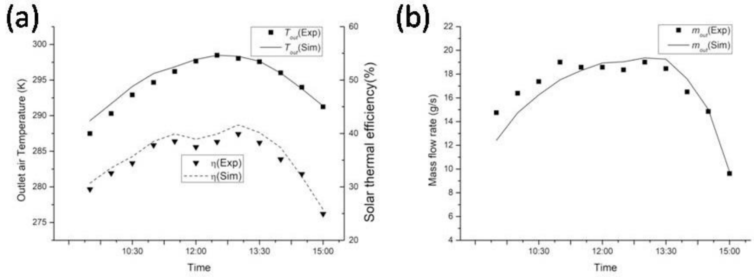

Fig. 2: Comparison between the simulations and experimental data for (a) Air mass flow rate; (b) Outlet air temperature and solar efficiency

4. Results

In order to evaluate the thermal performance of the Trombe wall with venetian blind structure for different operational parameters in summer and transition seasons, a series of simulations were performed using the established CFD model. The CFD modeling evaluates the effects of the operational parameters (e.g., slat angle, position of the slats in the cavity, inlet vent area and outlet vent area) on the thermal performance of the Trombe wall in the summer mode and transition season mode. The results are presented below.

4.1. Summer mode

In the summer mode, the Trombe wall operates with both outdoor inlet vent and outdoor outlet vent open. The solar radiation absorbed by the venetian blinds and inner wall heats up the air in the cavity, leading to a driving force for the airflow. The air flow through the cavity would help remove the heat from the south wall, resulting in a reduction in the cooling load.

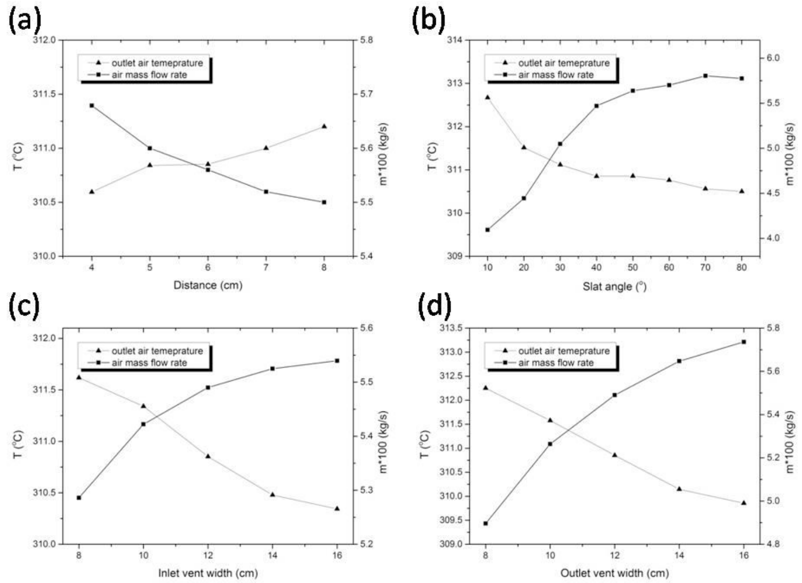

Fig. 3: Air mass flow rate and outlet air temperature as a function of: (a) slat position (distance between the slats and inner wall); (b) slat angles; (c) the area of the inlet vent; (d) the area of the outlet vent in summer mode.

The change of the slats position would lead to the variation of the Trombe wall thermal performance and the results are illustrated in Figure 3(a). It is found that the induced air mass flow rate decreases (from 0.057 to 0.055kg/s) as the distance between the slats and wall increases from 4cm to 8cm. Meanwhile, it can be seen that the outlet air temperature slightly rises (from 37.4 to 38.0 ºC) with the distance. This phenomenon occurs by the reason of increasing the distance between the slats and inner wall resulting in the increase of the heat loss to the ambient, which would consequently lead to decrease of air mass flow rate. However, the trend is completely different that the air mass flow rate increases and the outlet air temperature decreases with the distance in winter space heating mode as has been reported in the previous research [9]. Considering the performance of both summer wall cooling and space heating, the venetian blind is recommended to be set in the middle of the Trombe Wall.

The thermal performance of the Trombe wall would be influenced by the slat angle. While keeping the above wall structure and boundary conditions constant, simulation was carried out using the established CFD model. Figure 3(b) shows the air mass flow rate and the outlet air temperature for different slat angles. It can be seen that increasing the slat angle would lead to increase in the air mass flow rate (from 0.0409 to 0.058kg/s) and decrease in outlet air temperature (from 39.5 to 37.3 ºC). The thermal performance of the wall would be also depend on the area of the inlet and outlet vents. Figure 3(c) and (d) show the air mass flow rate and outlet air temperature versus the area of the inlet and outlet vents. It can be seen that a larger area of the vents yields an enhanced induced air mass flow rate. And the increasing of the air mass flow rate would decrease the outlet air temperature. It can also be found that the area of the outlet vent plays a greater impact than the area of the inlet vent does.

4.2. Transition season mode

At transition season mode, the Trombe wall operates with the indoor inlet vent and outdoor outlet vent open while with other vents closed. The indoor air comes into the air cavity through the indoor inlet vent and goes to the outdoor environment through the outdoor outlet vent. And consequently, the indoor air will move to the outdoor while the outdoor fresh air flow into the indoor environment, thus leading to the promotion of natural ventilation and reduction of cooling load.

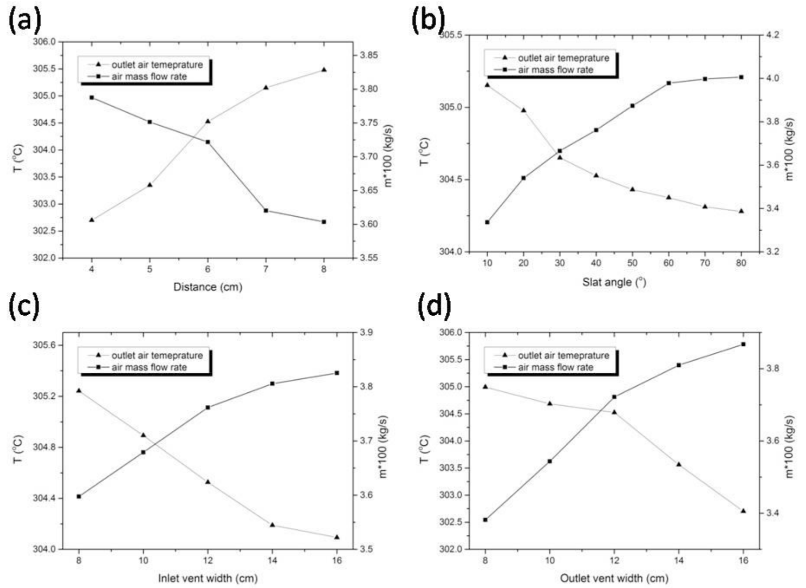

Fig. 4: Air mass flow rate and outlet air temperature as a function of: (a) slat position (distance between the slats and inner wall); (b) slat angles; (c) the area of the inlet vent; (d) the area of the outlet vent in transition season mode.

Figure 4(a) shows the Trombe wall thermal performance while the position of the slat is moved. As can be seen increasing the distance between the slats and the inner wall would lead to decrease in the air mass flow rate(from

0.038 to 0.036kg/s) and increase in the outlet air temperature (from 29.5 to 32.3ºC). The trend is similar to that at summer mode and different from that at winter space heating mode. The phenomenon can also be explained as same as mention before in 4.1 section.

Figure 4(b) shows the thermal performance of the Trombe wall with different slat angles at transition season mode. It can be seen the air mass flow rate increases (from 0.033 to 0.040kg/s) with the slat angle increases from 10º to 80º, while the outlet air temperature decreases (from 32.0 to 30.9ºC) with the slat angle increases. The trend is different from the winter space heating performance, in which higher slat angle results in decrease in solar thermal efficiency. The influence of the area of the inlet and outlet vents on the thermal performance is shown in Figure 4(c) and (d). As can be seen the larger area of the air inlet and outlet vents would results in the higher air mass flow rate and lower outlet air temperature. And the outlet vent area plays a greater influence on the thermal performance of the Trombe wall than the inlet vent area does, while is also observed at summer mode.

5. Conclusion

Trombe wall equipped with venetian blind provides free space heating in winter, sunshade in summer and natural ventilation in transition seasons, by harvesting solar energy. The thermal performance of the Trombe wall in summer and transition seasons was investigated with a CFD model. The present model has been validated with the experimental data. The effects of the Trombe wall operational parameters (e.g., slat angle, position of the slats in the cavity, inlet vent area and outlet vent area) on the thermal performance have been obtained for the summer mode and transition season mode. The research findings enable better understanding of the cooling effect of such a passive solar technology, and hence contribute to energy saving in the building sector.

Proper position of the venetian blind can cause significant increase in the ventilation. As the distance between the slat and the wall increases, the induced air mass flow rate slightly increases while the outlet air temperature drops in the summer and transition seasons. For a given solar radiation received by the slats, higher slat angle will lead to increase in the air mass flow rate and decrease in outlet air temperature. The effects of the venetian blind position and slat angle on the thermal performance in summer and transition seasons are completely different in comparison with the operation for space heating performance in winter. Moreover, the air mass flow rate increases with the vent area. The natural convective air flow rate is more sensitive to the area of the outlet vent than that of the inlet vent.

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