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Numerical Investigation of the Air Flow in a Novel PV-Trombe Wall Based on CFD Method

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The natural ventilation in a novel built-in photovoltaic-Trombe wall (BiPV-TW) was numerically simulated by computational fluid dynamics (CFD) method. The effect of solar radiation, channel width and height on the air flow pattern and ventilation rate was analyzed. Results showed that the solar radiation, channel width and height influenced the ventilation rate remarkably. As the solar radiation and BiPV-TW height increased, the ventilation rate increased. As the channel width increased from 0.1 m to 0.4 m, the ventilation rate monotonously increased. However, when the channel width exceeded 0.5 m, the reverse flow was formed in the tope zone and the ventilation rate decreased. A maximum air volume flow rate was achieved when the channel width was approximately equal to 0.4 m in a 3 m tall model. The channel width was the dominant factor that influenced the flow pattern in the channel. When the channel width was smaller than 0.4 m, the airflow was thermally stratified laminar flow. When the channel width exceeded 0.5 m, thermally stratified flow disappeared due to the reverse flow formed in the top zone and the laminar flow became turbulent.

1. Introduction

Green building and sustainable architecture are known to be energy-conserving and environment-protective by utilizing new and renewable energies for heating, ventilation and air conditioning. Trombe wall and solar chimney are both passive solar technologies to provide ventilation and/or heating to buildings based on natural ventilation principle. Su et al (2011) and Saadatian et al (2012) have reviewed the recent development of solar chimney and Trombe wall. A classical Trombe wall is constituted of a massive wall installed at a small distance from a glazing. Solar radiation passes through the glazing and is absorbed at the absorber wall surface. The air in the channel is then heated by convection and radiation from the absorber. The decrease in density experienced by the air causes it to rise, whereupon it is replaced by air from below, i.e. from the attached room. The rate at which air is drawn through the room depends upon the buoyancy-force experienced, (i.e. dependent upon the temperature differential), the resistance to flow through the chimney, and the resistance to the entry of fresh air into the room. Many authors reported their studies on different Trombe walls. Bansal et al (2005) developed a mathematical model for predicting airflow velocity in a solar chimney through predicting temperature of the absorber, air in flow channel and glass cover. Ong et al (2003) proposed a steady heat transfer model of a solar chimney based on a thermal resistance network and the temperatures of the glass glazing, the absorber wall, the temperature and velocity of the induced air flow in the chimney were predicted. Gan (2010) simulated the ventilation and heat transfer in a Trombe wall and further correlated general expressions for the calculation of air flow and heat transfer rates (Gan, 2011). Zamora et al (2009) numerically studied the optimum wall-to-wall space in a solar chimney. PV-Trombe wall is a new invention and can convert solar radiation into electricity and heat simultaneously. In a PV-Trombe wall, the front side of the glazing is composed of photovoltaic panels that simultaneously convert solar radiation into heat and power. Ji et al (2007) proposed heat transfer model for this type of PV-Trombe wall based on energy balance. However,

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the PV panel on the front cover hinders the penetration of solar rays into the Trombe wall channel between the walls and glazing (Himanshu, 2009). Therefore, the efficiency of the Trombe wall is reduced in terms of heat gain (Jiang et al, 2009). The study revealed that installing PV panels over the glazing reduces the thermal performance of the Trombe wall up to 17 % (Sun et al, 2011). This reduction is due to the obstructed penetration of the sun's rays into the mass wall. When the glazing was fully covered by PV cells, the total solar utilization rate of the PV-Trombe wall was reduced 5 % even when the solar-electricity was taken into account (Sun et al, 2011). Numerical results (Koyunbaba et al, 2012) also showed that the air temperature in both the Trombe wall channel and the room decreased, which resulted in a decreased ventilation performance. Therefore, the efficiency of the Trombe wall is reduced in terms of heat gain. However, this type of Trombe wall generates electricity, which is considered a benefit.

In order to improve the solar efficiency of Trombe wall, a novel built-in photovoltaic-Trombe wall (BiPV-TW) was proposed in this paper. In the present model, the PV cells were installed on the absorber wall surface other than on the inner surface of the glazing. The solar radiation could totally penetrate the glass cover and enter the Trombe wall channel. Then the solar radiation is absorbed by the PV cells on the absorber wall and converted into both electricity and heat. The air flowing over the PV cells was heated via convection and formed the natural ventilation. Computational fluid dynamics (CFD) calculation was used to simulate the air flow in the channel.

2. Models

2.1 BiPV-Trombe wall model

Figure 1 shows the physical and simplified model of the BiPV-TW system. The physical model consists of exterior glass cover, PV panels attached to the interior absorber wall and separated by insulating layer, an air channel between the cover and PV panels with air openings. Solar radiation passes through the glass cover and impinges on the PV panels. A part of the solar energy is then converted to electricity by the PV panels and the remained solar radiation is converted into heat which increases the PV panels' temperature. The air flowing over the PV panels is then heated by natural convection. Due to the stack effect, the heated air generates natural ventilation in the Trombe wall space and the PV panels are then effectively cooled by the air flow, as a result, the PV cell efficiency for power generation is maintained due to the cooling by the natural ventilation.

The solar radiation intensity and the heat flux impinging on the PV panels are noted as q_1 and q_2, respectively. The channel width is noted as *b* which varies between 0.1m to 0.6m and the channel height is noted as *H* varying from 1m to 6m. A horizontal inlet and a vertical outlet are set at the bottom and top of the Trombe wall and the opening sizes equal to the channel width. It is also assume that the bottom wall of the Trombe wall is adiabatic, as showed in Figure 1. However, when the outlet is horizontal, the local air flow near the outlet will be influenced, like local vortex may form there and so the local heat transfer may be influenced and should be further studied.

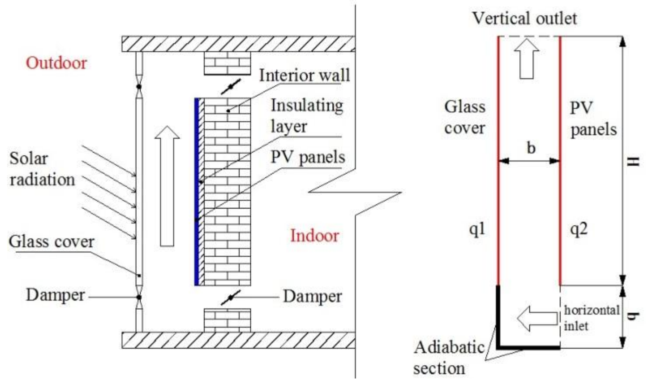


Figure 1: Physical model and simplified model of the BiPV-TW

2.2 Numerical model

Air flow through a tall ventilation channel would likely involve both laminar and turbulent flow and the RNG κ-ε turbulence model was employed for modeling of both strongly turbulent and less turbulent flow. Discrete Ordinate (DO) radiation model was used to calculate the radiation heat transfer between the glass and the panels. Since the temperature difference between the inlet and outlet of the model system is not expected to be very high, the usual Boussinesq approximation is adopted. Under this assumption, general equations for the simplified two-dimensional incompressible steady-state flow take the following form:

$$div(\rho V\Phi) - div(\Gamma_{\Phi} grad\Phi) = S_{\Phi} \quad (1)$$

where Φ represents the mean velocity component v_i in x_i direction, turbulent parameters and mean enthalpy, Γ_ϕ is the diffusion coefficient and S_ϕ is the source term for variable Φ.

A structure, mapped mesh with quadrilateral 2D elements was built in the code. The enhanced wall treatment was selected due to the large changes of temperature and pressure gradient near the wall region. In order to ensure the accuracy of the numerical results, a grid independence study was performed by changing the number of the nodes in the horizontal and vertical direction. The horizontal inlet and vertical outlet were set as pressure inlet and pressure outlet respectively, a constant, uniform heat flux was imposed on both glass cover and PV panels in this simulation. The second-order upwind differencing scheme was adopted for the convective terms of the momentum and energy transport equations, and the SIMPLE method was used to solve the momentum and continuity equations. The simulations of air flow and heat transfer in vertical channel of BiPV-TW were conducted using the commercial CFD code, FLUENT version 6.3 (2006).

3. Results

3.1 Comparison of the present CFD results to published data

Gan (2010) numerically calculated the air flow in a classical Trombe wall by RNG κ-ε turbulence model and compared his predicted data to measured data of mass flow rate of air and validated the RNG κ-ε turbulence model was suitable for the simulation. At the beginning of the present study, the above numerical model and boundary conditions were used to calculated the air flow in the same Trombe wall which Gan (2010) has studied and validated by comparison of the present predicted flow rate to the date predicted by Gan (2010), as showed in Figure 2 and Figure 3. The heat distribution ratio was defined as the ratio of the heat flux from the wall with the inlet (the right wall) to the total heat flux from both walls (Gan, 2010). Good agreement between the current results and reference data showed that the present model was reasonable for the further calculation of the air flow in the novel built-in photovoltaic Trombe wall.

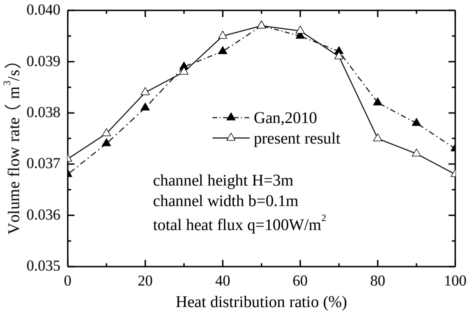


Figure2: Comparison of the present calculated flow rate to reference data

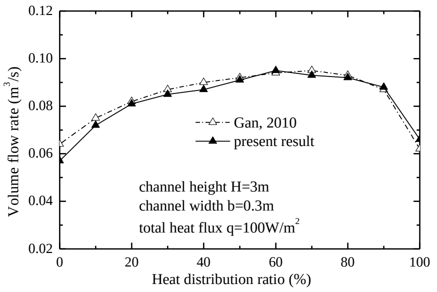


Figure 3: Comparison of the present calculated flow rate to reference data

3.2 Effect of solar radiation on air flow behavior inside the BiPV-Trombe wall

The air flow determines the heat transfer on the PV panel surfaces and the ventilation rate of the Trombe, which influence the total efficiency of solar utilization and ventilation rate of the built-in PV Trombe wall. The air flow is influenced by several parameters, such as the solar radiation, the channel height and width. The solar radiation provides the energy to heat the air and induces the rising flow. Figure 4 to Figure 7 present the air flow temperature and pressure distribution, flow vector and the volume flow rate inside the BiPV-Trombe wall channel.

When the geometric sizes of the BiPV-Trombe wall are given, increased solar radiation will increase the heat transferred via convection from the PV cells to the air flowing over the PV cells. As showed in Figure 4, when the solar radiation increased, the thickness of the thermal boundary layer of the air near the right surface (the PV cells) increased. Once it received more heat, the air will rise at higher velocity, leading to increased flow rate and lower local pressure. Figure 5 presents the local air velocity distribution along the channel width at the height level of 1.5 m. As the solar radiation increased, more heat was transferred to the air flowing over the PV cells by natural convection and the thermal buoyancy therefore increased, leading to a higher rising velocity of the air, as showed in Figure 5. Figure 6 presents the ventilation rate vs. solar radiation intensity. The ventilation rate was defined as the product of the channel cross-section and mean outlet air velocity. As the solar radiation increased, the ventilation rate increased.

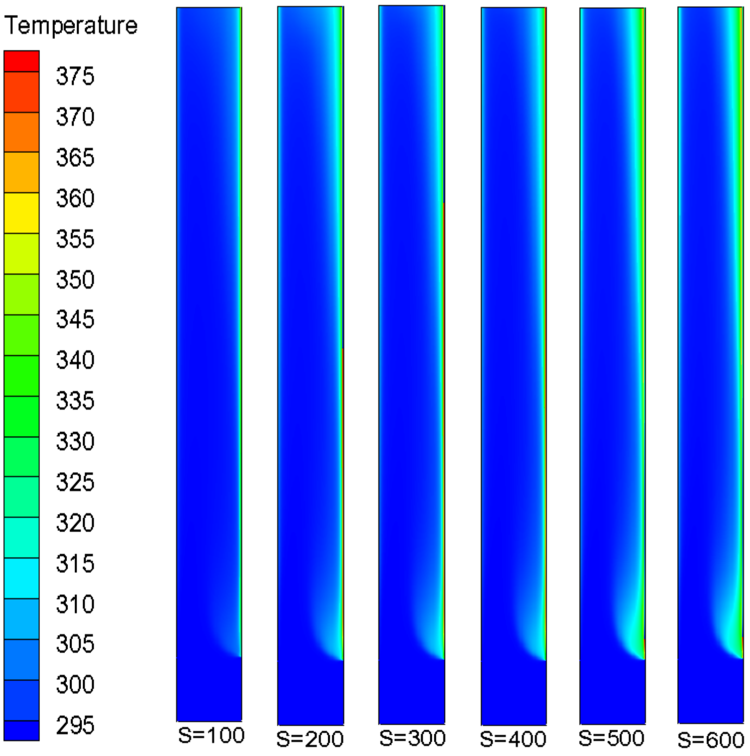
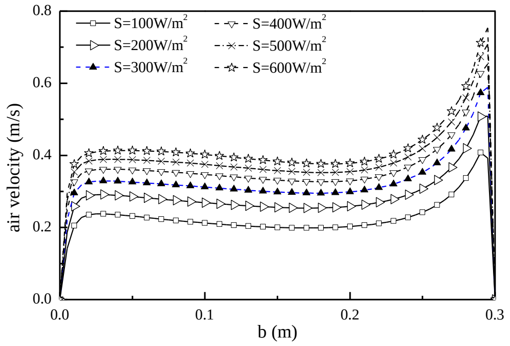


Figure 4: Temperature in the BiPV-Trombe wall channel (K) (H=3 m, b=0.3 m, S is the solar radiation, W/m^2)



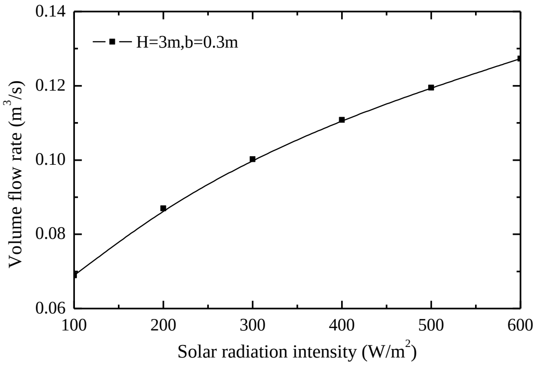
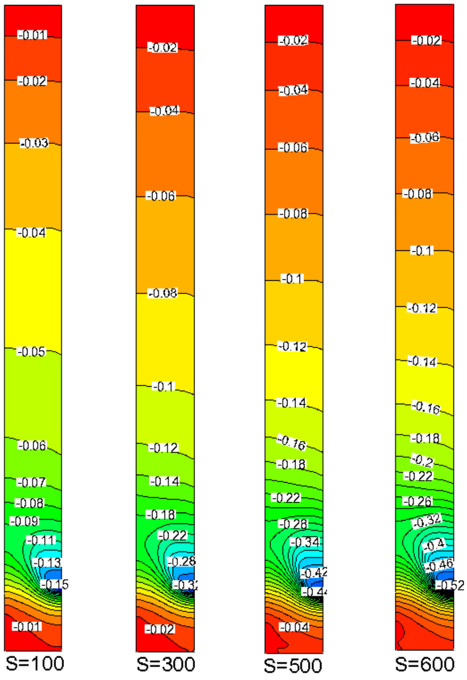


Figure 5: Air velocity along channel width at the height level of 1.5m

Figure 6: Ventilation rate vs. solar radiation intensity

Figure 7 presents the pressure contours of the air in the channel when the channel was set 0.3 m and the solar radiation varied from 100 W/m^2 to 600 W/m^2. It was seen that the static pressure of the air was always negative due to the rising flowing of the air through the channel. The higher the absolute value of the static pressure was, the higher the air rising velocity became. Therefore, as the solar radiation increased, the air received more heat and the rising flow of the air was enhanced. Figure 7 agreed well with the result s showed in Figure 4 and Figure 5. The obvious feature of the pressure contours was that the static pressure isolines were almost horizontal above the inlet, which, at least partly, indicated the flow was laminar rather than turbulent. Solar radiation was not the major factor to influence the flow state of the air in the channel when the channel width was fixed. At the inlet there was always a local vortex, as showed in Figure 8. The rising airflow along the PV panels forms a natural convection boundary layer which was basically laminar.



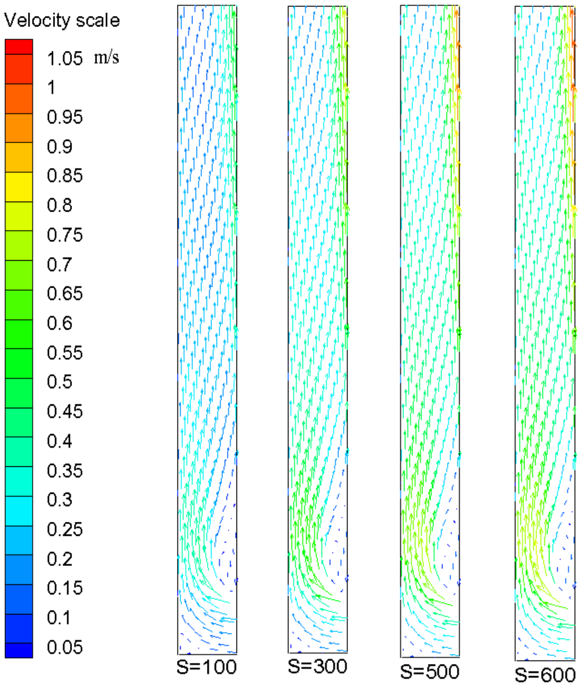
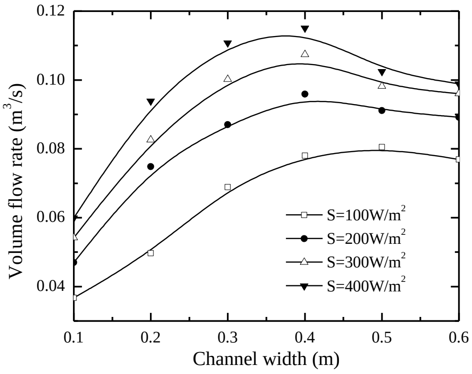


Figure 7: Pressure contour (Pa) (H=3 m, b=0.3 m, S is the solar radiation, W/m^2)

Figure 8: Velocity vector (m/s) (H=3 m, b=0.3 m, S is the solar radiation, W/m^2)

3.3 Effect of channel width

Previous studies showed that channel width was the major factor which influenced the ventilation rate of the classical Trombe wall. Gan (1998) calculated the natural ventilation of the classical Trombe wall and found that the air flow rate increased with the channel width when the channel width was between 0.05 to 0.4 m when the width of the inlet and outlet opening was set to the same as the channel width. Burek and Habeb (2007) experimentally measure the air flow rate in a classical Trombe wall and found the air flow rate increased with when the channel width increased from 0.02 m to 0.12 m. However, those authors did not study the cases when the channel width was more than 0.4 m. The effect of the channel width on the air flow in the BiPV-Trombe wall was simulated.



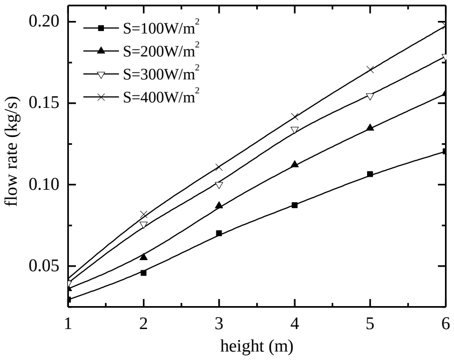


Figure 9: Volume flow rate vs. channel width (H=3 m)

Figure10: Volume flow rate vs. channel height (b=0.3 m)

Figure 9 presents the ventilation rate vs. channel width. As the channel width increased from 0.1 m to 0.4 m, the ventilation rate monotonously increased. The vector and pressure contour results indicated that reverse flow was not formed when the width was less than 0.4 m and the air flow was actually thermally stratified flow. However, when the width exceeded 0.5 m, the reverse flow was formed and the ventilation rate decreased.

3.4 Effect of channel height

The ventilation rate increased with the channel height as results, as showed in Figure 10. The flow in the channel was laminar and local vortex was not formed when the channel height increased, as showed by the flow vector in Figure 10. Therefore, the channel height was not a major factor to influence the air flow pattern.

4. Conclusions

CFD simulation was conducted to calculate the air flow and natural ventilation in a novel built-in PV-Trombe wall. The effect of solar radiation, the channel width and height was discussed. From the results the following conclusions could be drawn. As the solar radiation and BiPV-TW height increased, the ventilation rate increased. As the channel width increased from 0.1 m to 0.4 m, the ventilation rate monotonously increased. However, when the channel width exceeded 0.5 m, the ventilation rate decreased. A maximum air volume flow rate was achieved when the channel width was approximately equal to 0.4 m in a 3 m tall model.

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