A numerical Study of Trombe Wall for Enhancing Stack Ventilation in Buildings

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ABSTRACT: Natural ventilation is an important means to improve indoor thermal comfort and reduce the energy consumption. Trombe wall, as a type of solar chimney system, is an enhancing natural draft device, which uses solar radiation to heat the air inside the chimney, thereby converting the thermal energy into kinetic energy. In this paper, a parametric study has been carried out to predict mass flow rate, temperature field and velocity field for Trombe wall system under steady conditions. RNG $k-\varepsilon$ turbulence models and wall function methods were used. Grid independent studies were carried out to ensure essentially no changes after doubling the grids numbers. Suggestions for optimum construction design of Trombe wall were provided based on large numbers of simulation results. Results showed that there is an optimum ratio of chimney gap to height to achieve a maximum airflow rate, which is dependent on the inlet design and independent of solar radiation. Meanwhile, reverse flow can be observed at the outlet when the chimney gap increased to a certain value. Satisfactory correlation was obtained with other investigations.

Keywords: Natural ventilation; Trombe wall; Numerical simulation

1. INTRODUCTION

Saving energy and sustainable development are two themes in building constructions after the international energy crisis in 1973. Energy required for heating and cooling of buildings in approximately 30% of the total world energy consumption [1]. Natural ventilation and renewable energy utilization are widely used to improve the indoor air environment and reduce the energy consumption of air conditioning.

The indoor environment for summer is normally obtained by air conditioning or ventilation including mechanical ventilation and natural ventilation. Natural ventilation not only can save energy and life cycle costs, but also can alleviate the environmental burden from the by-products by energy consumption. The purpose of natural ventilation is to replace (or partly replace) the air conditioning systems in certain regions, climates and seasons in the year. Modern society, compared with primitive society and places, is characterized by high civilization level and advanced accommodations, involving heating supply for the severe winter and air conditioning for hot summer. However, the comfort for these building fully depends on the running machines and equipments. Once the power is cut off deliberately or accidents occur, modern functions of building will totally disappear. The annual summary report [2] of International Energy Agency (IEA) shows that for the well-insulated office buildings, a well-controlled and energy-efficient natural ventilation system can reduce more than 50% of energy requirement. Natural ventilation not only can overcome such problems as noises, SBS (sick building syndrome) and complicated routine maintenance and high energy consumption, but can be easily integrated into green buildings which provide a healthier and comfortable environment.

There are several kinds of new energy resources including wind power, water power, terrestrial heat, tide energy, solar and nuclear energy. In building construction, there are two modes of solar energy application for indoor thermal comfort. One is positive solar house, which uses the photovoltaic materials converting solar energy to electricity first. The application of positive solar houses is restricted because of high cost of photovoltaic materials. The other mode is passive solar house, which is increasingly applied in the world. How to make residential building healthy, comfortable with minimum costs is a big challenge for both architects and engineers. Proper building orientation and layout for surroundings, smart integration of indoor space and outdoor figures, and skilful selection of building materials, frame work and construction could not only reduce the heating energy for building in winter through collecting, maintaining storing and distributing solar energy, but also reduce the indoor temperature in summer through preventing solar radiation from indoor space. Warm winter and cool summer could be achieved by passive solar house. The building envelopes (roofs and side walls) will never be treated as passive thermal resistances, but as solar energy collectors. Passive solar heating in sunny district could reduce conventional heating cost by 70%, even in cloudy district 30% energy consumption can be saved in United States and Europe [3]. Since energy crisis in 1973, 200,000 residential buildings and

150,000 commercial buildings have been built up in America [3].

Trombe wall as one of effective means to enhance natural ventilation has been noticed and utilized since it integrates solar energy and natural ventilation organically. Trombe wall, as one type of solar chimney, is a natural draft device, which uses solar radiation to provide upward momentum to a mass of air, thereby converting the thermal energy into kinetic energy [4]. Under this kind of dynamic condition, the design temperature for thermal comfort can be increased up to 28°C, which can prolong the period for natural ventilation and reduce the times for running air conditioning. It can improve the indoor air quality by supplying outdoor fresh air and avoid the sick building syndrome due to exposure to air conditioning for a long time. Personal psychological needs to communicate with nature could be satisfied with natural ventilation to a large extent. It makes use of available solar energy to promote natural ventilation, cooling and heating. All this can promote the development of healthy buildings. With the increasing needs of ventilation systems in building which are efficient and in harmony with nature, is increasingly used in passive solar houses or hybrid ventilation systems. Replace night air conditioning system, remove the heat stored during the daytime in building and reduce the energy consumption of air conditioning for the next day.

In addition, the effects of Trombe ventilation would depend on climate conditions. In China, in spring and autumn, outdoor air condition could satisfy thermal comfort for indoor environment, which will drastically reduce energy consumption during these periods. The outdoor temperature during the night is much lower than that in the daytime, so that night air conditioning can be replaced by natural ventilation, which may reduce the heat storage in the daytime and reduce the energy consumption further for the next day.

In this paper, different Trombe wall models with various height, opening width, air gap and solar intensities have been simulated with CFD software--FLUENT. During the process of simulation, the density of grids has been increased until there is almost no variation between the two results (the error should be in 1%). Thus, the grid independent result has been obtained. Temperature field and velocity field in the Trombe wall have been analyzed.

2. METHODOLOGY

2.1 Turbulence model

For Trombe wall, two-dimension turbulence model has been selected since the width of the model is much smaller than the length of the model, which is the characteristic of the calculation range of the model. RNG model, which can deal well with low Reynolds number and near wall flow method, with the enhanced wall function calculation method, which demands very fine mesh for near wall $y^+ \approx 1$, has been selected.

2.2 Calculation range

The calculation ranges of two dimension model W (width)×H (height) are as following. W=0.1m~0.6m, H=1.0m~3.0m. Heat fluxes which are the part of solar radiation transmitted through the windows in heat storage wall are separately 100W/m^2, 200W/m^2, 300W/m^2, 400W/m^2.

2.3 Simulation method

A number of different configurations of Trombe wall have been simulated. To find the rules for the variation of flow rate of solar chimney, the effects of heat fluxes S1 , S2 , chimney height H , air gap width W, the width of inlet and outlet A_{in} , A_{out} on ventilation flow rate have been investigated.

(1) Keeping the constant of W, Tin, Ta, S1, S2, A_{in}, A_{out}, investigate the effects of chimney height H on mass flow rate m ;

(2)Keeping the constant of H , Tin , Ta , S1 , S2 , A_{in} , A_{out} , investigate the effects of air gap W on mass flow rate m ;

(3) Keeping the constant of W, H, Tin, Ta, S1, S2, investigate the width of outlet and inlet A_{in}, A_{out} on mass flow rate m ;

(4) For each condition above, the effects of heat fluxes S1, S2 on mass flow rate m have been investigated.

Actually, each variable in real project varies in a certain range. However, it is difficult to get the general variation trend of mass flow rate within the certain range. In order to give attention to the real project and theoretical investigation, the ranges of variables have been extended in the simulation. Some extreme conditions have been calculated. Therefore, the variation rules for mass flow rate induced by Trombe wall could be recognized more clearly and the design guidelines for Trombe wall have been provided.

3. RESULTS

3.1 Mass flow rate

The mass flow is affected by many parameters, such as solar radiation, air gap, the width of inlet and outlet and Trombe wall height. The effect of width of air gap on mass flow rate is the most complicated.

3.1.1 The effect of solar radiation

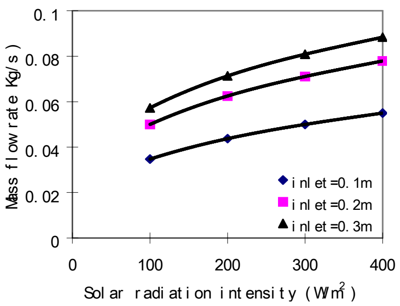


Figure 1: The variation of mass flow rate with solar radiation (H=3m; W=0.2m)

As shown in Fig. 1, it can be seen that the mass flow rate is increasing with the increase of solar radiation intensity. As the main power for solar chimney, solar radiation is transmitted through the clear glass and then is mainly absorbed by the heat storage wall to heat the air inside. The hot air will goes up by the stack effect, which promote the indoor natural ventilation. With the increase of solar radiation intensity, the heat gain of the heat storage wall has been increased, the temperature of air inside the chimney has been increased, the density difference has been increased, the stack effect is more obvious and the mass flow rate has been much increased.

3.1.2 The effects of air gap width

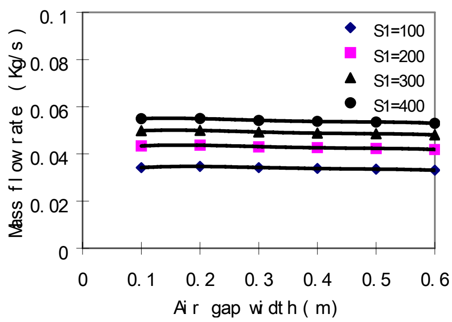


Figure 2: the variation of mass flow rate with air gap width (H=3m; Inlet=0.1m)

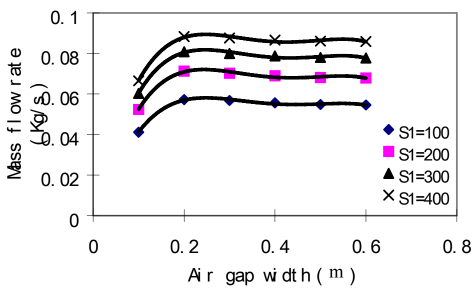


Figure 3: the variation of mass flow rate with air gap width (H=3m, Inlet =0.3m)

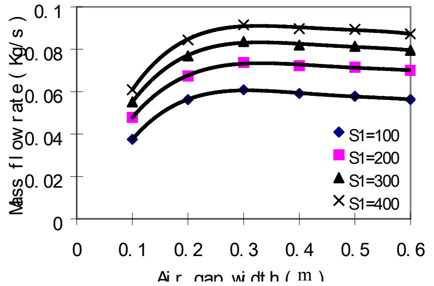


Figure 4: the variation of mass flow rate with air gap width (H=3m, Inlet =0.5m)

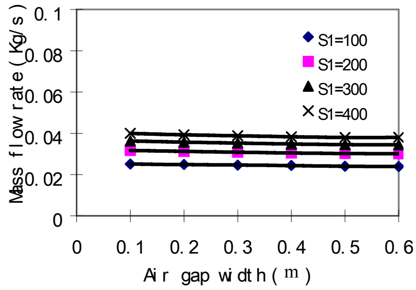


Figure 5: the variation of mass flow rate with air gap width (H=2m, Inlet =0.1m)

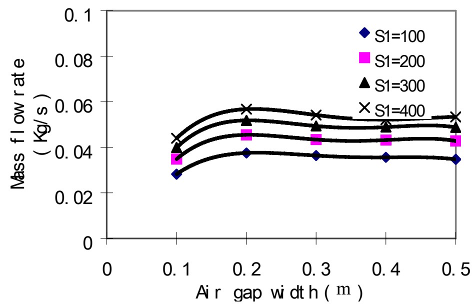


Figure 6: the variation of mass flow rate with air gap width (H=2m, Inlet =0.3m)

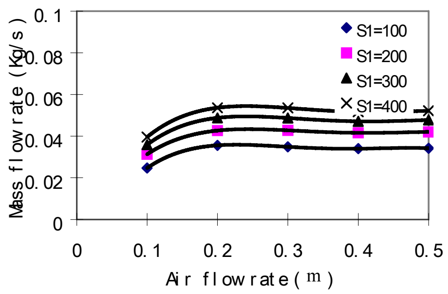


Figure 7: the variation of mass flow rate with air gap width (H=2m, Inlet =0.4m)

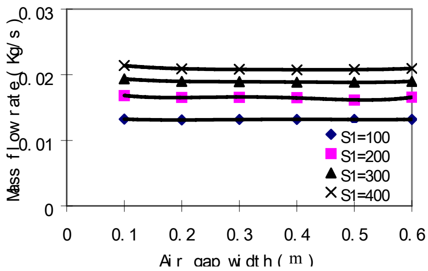


Figure 8: the variation of mass flow rate with air gap width (H=1m, Inlet =0.1m)

The variation of mass flow rate in the with the air gap width has been shown in Fig. 2-8. It has been proved that there is an optimum ratio of air gap width to chimney height through a number of simulations. But the optimum ratio is dependent on the dimension of inlet and outlet for solar chimney. When the Trombe wall height is 3m and the width of inlet is 0.1m, mass flow rate of Trombe wall will reach the maximum under the condition that air gap width is about 0.2m for 3m high solar chimney. With the increase of inlet width, the variation of mass flow rate with air gap width is much obvious. The optimum air gap width is 0.3m when the chimney height is 3m. When the chimney height is 2m and the inlet width is 0.1m, the optimum air gap width is 0.1m. With the increase of inlet width, the optimum air gap width is 0.2m for 2m high solar chimney. When the chimney height is 1m and inlet width is 0.1m, the optimum air gap width is 0.1m.

With the increase of air gap width, the flow resistance is decreasing and the mass flow rate is increasing. Until the air gap width is increasing to a certain value, air flow status will change from the limited space flow to unlimited space flow and backflow will occur around the outlet of solar chimney. Mass flow rate will not increase with the increase of air gap width under this condition. In contrast, the air flow rate for natural ventilation will decrease result from backflow.

In the same time, it can be seen that mass flow rate of Trombe wall is almost not affected by the variation of air gap width when the inlet width is 0.1m. This could be attributed to that the pressure losses in the whole system are mainly caused by the pressure losses of inlet and outlet. The pressure loss due to friction is much less than the inlet and outlet pressure losses, although the friction pressure losses are decease with the increase of air gap [5].

3.1.3 The effects of inlet width

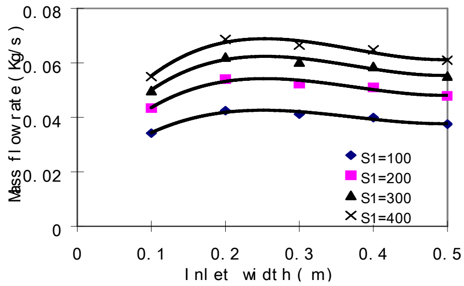


Figure 9: the variation of mass flow rate with inlet width (H=3m; W=0.1m)

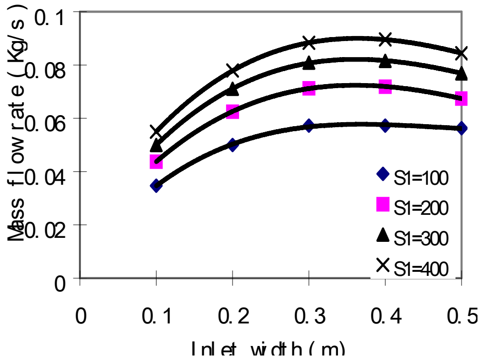


Figure 10: the variation of mass flow rate with inlet width (H=3m; W=0.2m)

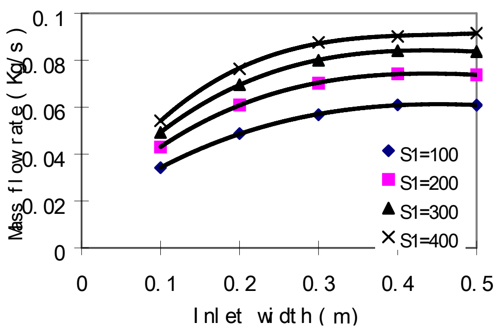


Figure 11: the variation of mass flow rate with inlet width (H=3m; W=0.3m)

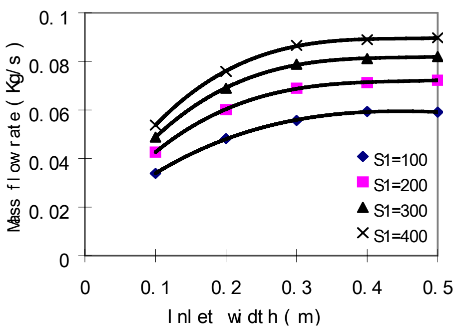


Figure 12: the variation of mass flow rate with inlet width (H=3m; W=0.4m)

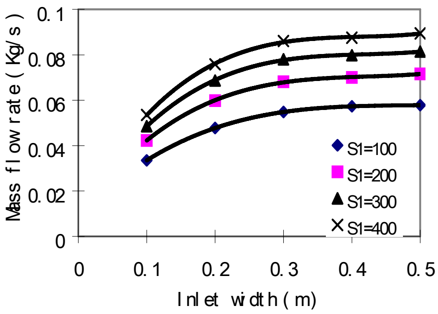


Figure 13: the variation of mass flow rate with inlet width (H=3m; W=0.5m)

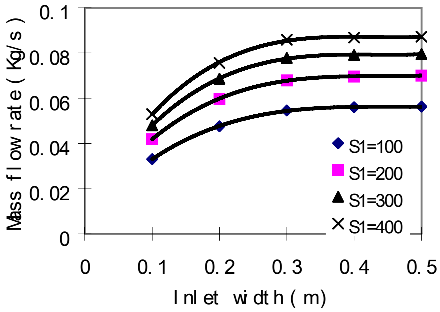


Figure 14: the variation of mass flow rate with inlet width (H=3m; W=0.6m)

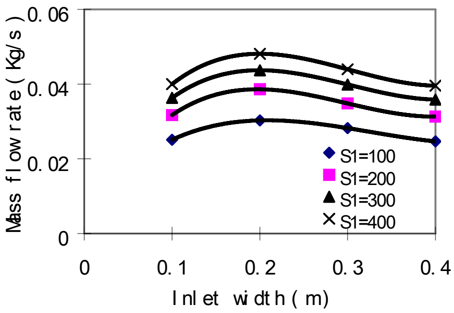


Figure 15: the variation of mass flow rate with inlet width (H=2m; W=0.1m)

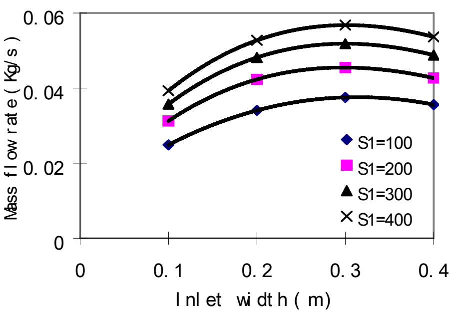


Figure 16: the variation of mass flow rate with inlet width (H=2m; W=0.2m)

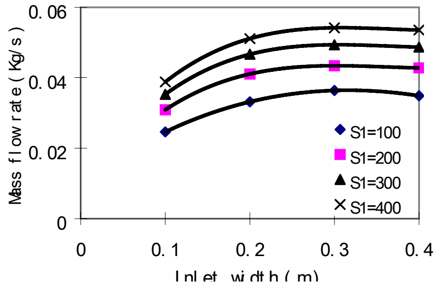


Figure 17: the variation of mass flow rate with inlet width (H=2m; W=0.3m)

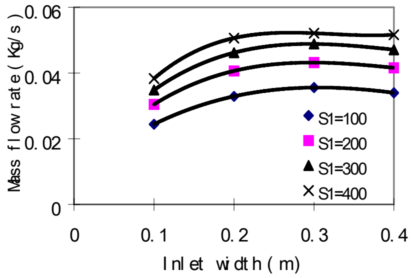


Figure 18: the variation of mass flow rate with inlet width (H=2m; W=0.4m)

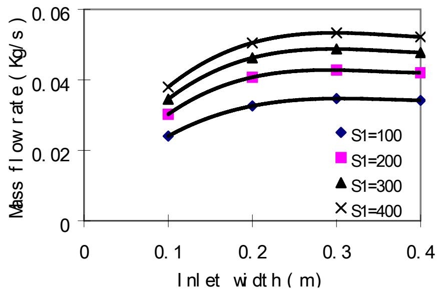


Figure 19: the variation of mass flow rate with inlet width (H=2m; W=0.5m)

From the results shown in Fig. 9-19, it can be seen that with the increase of inlet width, the mass flow rate of goes up to the maximum and then go down. Furthermore, the maximum value is related to chimney height and the width of air gap. With the increase of opening width, the pressure losses of outlet and inlet are decreasing, but the area of heat storage wall is decreasing. Therefore, the maximum ventilation rate will be obtained when the two have been balanced. The optimum ratio of opening width to height, which is related to air gap width, is about 3/20 when the air gap is more than 0.1m.

3.1.4 The effects of Trombe wall height

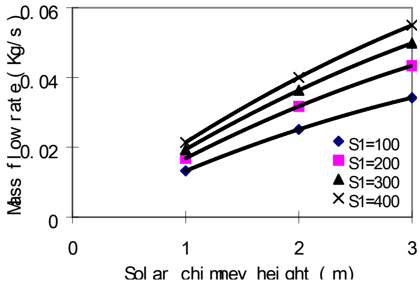
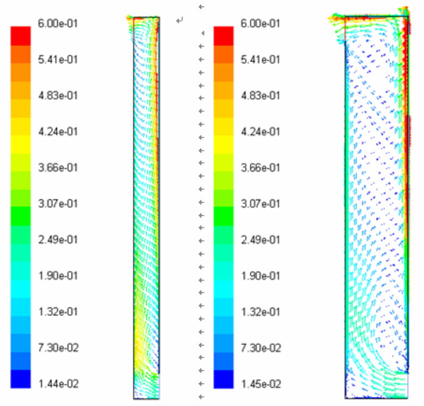


Figure 20: the variation of mass flow rate with the variation of chimney height (Inlet =0.1m; W=0.1m)

Fig. 20 describes the variation of mass flow rate with the variation of Trombe wall height. From the results, it can be seen that mass flow rate is obviously increasing with the increase of Trombe wall height. This is mainly due to the strong increase of stack effect. There are two main reasons for the increase of stack effect. Firstly, the surface area of heat storage wall increases with the increase of chimney height. Therefore, more solar radiation has been obtained and air temperature inside the has been increased. As a factor of stack effect, density difference between outside and inside increases. Secondly, chimney height is one factor for stack effect. Therefore, it can be said that the increase of height brings the obvious increase of mass flow rate.

3.2 Velocity filed

From the velocity field profile illustrated in Fig. 22-23, it can be seen that distribution of air velocity along the air gap width for Trombe is non-uniform. Air velocity near heat storage wall is much higher than that in the middle. Air velocity inside the will decrease with the increase of air gap width and increase with the increase of solar radiation intensity. Reverse flow phenomenon has been clearly shown in Fig.21 (b). Backflow occurs when air gap width increased to a certain value. With the increase of air gap with, the intensity of backflow increases.



(a) (b)

Figure 21: velocity profile for Trombe solar chimney in two different air gap width chimney (chimney height 3m, inlet width 0.2m and heat flux for heat storage wall 200W/m^2) (a)air gap width 0.2m (b)air gap width 0.5m

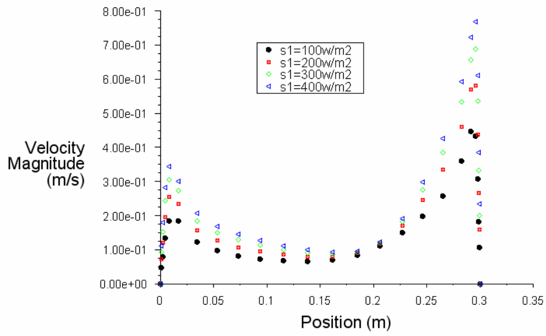


Figure 22: velocity profile for Trombe wall along air gap width(chimney height 3m, inlet width 0.2m, air gap width 0.3m, Heat fluxes for heat storage wall100, 200, 300, 400W/m^2)

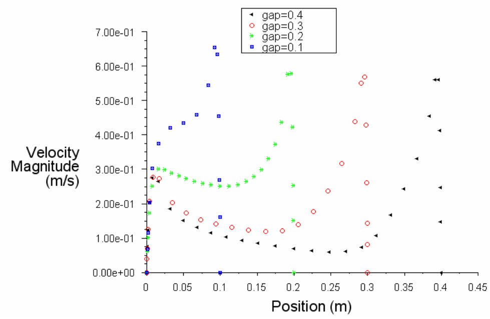


Figure 23: velocity profile for Trombe wall along air gap width (chimney height 3m, inlet width 0.3m, air gap width 0.1, 0.2, 0.3, 0.4m)

3.3 Temperature field

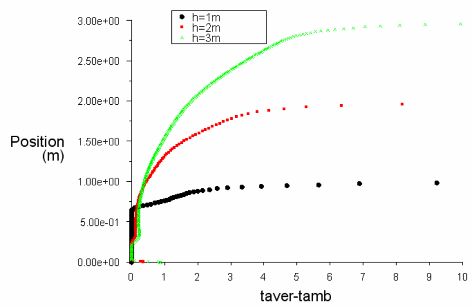


Figure 24: temperature profile for Trombe wall solar chimney along chimney height (inlet width 0.2m, air gap width 0.2m, solar radiation 200W/m^2, chimney height 3, 2, 1m)

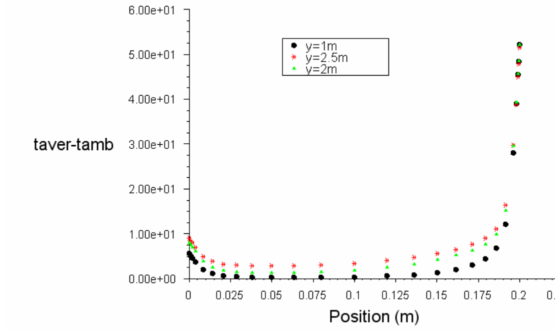


Figure 25: temperature profile for Trombe wall solar chimney along air gap width(chimney height 3m, inlet width 0.2m, air gap width 0.2m, solar radiation 200W/m^2)

From the temperature field profile shown in Fig.24-25, it can be seen that air temperature inside the Trombe increases along the chimney height and is non-uniform along air gap width. Temperature is quite high near heat storage wall. With the increase of solar radiation intensity and height, air temperature inside increases.

4. CONCLUSION

There is an optimum ratio of air gap width and chimney height for Trombe wall to obtain the maximum ventilation rate, which is related to the opening design. Approximately, it can be considered the optimum air gap width is equal to 1/10 of chimney height in most cases. Furthermore, it can be seen from the results that the optimum air gap width to obtain the maximum ventilation rate is about 0.2-0.3. The widths of opening have big effects on ventilation rate for Trombe wall solar chimney. There is optimum opening width for maximum ventilation rate, which is related to the chimney height and air gap width. With the increase of air gap width and chimney height, the optimum value increases. For the purpose of ventilation and optimum design of Trombe wall solar chimney, chimney height is better than 1m , the optimum ratio of air gap width to height is about 1/10, opening width is better than 0.1m , and the optimum ratio of inlet to height is about 3/20.

ACKNOLEDGMENTS

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NOMENCLATURE

S_1	——Uniform heat flux for heat storage wall(W/m^2)
S_2	——Uniform heat flux for glazing(W/m^2)
H	——Solar chimney height(m)
W	——Air gap width(m)
A_{in}	——Inlet width (m)
A_{out}	——Outlet width (m)
m	——Mass flow rate (kg/s)

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