Experimental Investigation of Natural Convection in Trombe Wall Systems

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Abstract: In this paper, experiments with a passive solar building with Trombe wall in the north cold climate are carried out and discussed, and the natural convection heat transfer process has been investigated. The relativity of the factors affecting indoor air temperature is analyzed with the stepwise regression method. The results indicate that thermo-circulation induced by the stack effect is the dominant factor. The natural convection in the channel is fairly complex; it changes from the laminar flow to the turbulent flow and the turbulent flow covers at least half the height of massive wall during the normal circulation. The flow in the channel is considered as natural convection between vertical plates. Analyzing the natural convection heat transfer process with the Rayleigh number and the mean Nusselt number, the thermo-circulation can be divided into three periods in the daytime: coast up, maintenance and weaken. During the maintenance period, the changes of the solar radiation intensity and surface temperatures have little effect on *Nu* number.

Key words: passive solar building; Trombe wall; natural convection.

1. INTRODUCTION

Considerable interest has been recently observed in passive solar heating systems, which combine the solar collection and thermal storage into the building structure and distribute the heat by natural methods. The Trombe wall is a kind of passive solar heating systems used for space heating.

The Trombe wall system consists of the south massive wall and a glass cover. Vents are located at both the top and the bottom of the wall. Solar heat, absorbed by the darkened massive wall surface, is transferred to the room by heat convection and conduction. Relatively cool air in the room, drawn through the bottom vents, is heated up as it passes thought the channel and then delivered into the room through the top vents by stack-effect. The thermo-circulation provides a direct heat path to the room, while the conduction through the wall has a time delay. These two paths are interactive.

Trombe[1] (1976), who established the initial experiments in this field at Odeillo of France, suggested that the mass flow limit should be caused as a result of turbulent flow along the entire height of the channel. The horizontal air inlet may be the probable cause of the turbulence. Experimental results by Hocevar et al. [2] (1979) showed that the natural convection flow processes occurring in the channel were fairly complex. The velocity and temperature profiles in the channel were the functions of the geometrical features of the wall and the ambient conditions. The investigations indicated that most of the flow patterns encountered during their experiments (with channel width size varying from 2.5 to 20 cm and Trombe wall high 2.2m) were laminar in nature. Akbari et al.[3, 4] (1979 and 1984) performed a theoretical analysis of the flow in the channel for both the laminar and the turbulent cases. The flow was considered as natural convection between the two vertical plates. Theoretical and experimental investigations by W. Smolec et al. [5] (1993) revealed that convection heat transfer in the Trombe channel depends upon the bottom vents was similar to the convection heat transfer in the entrance region in air ducts, instead of on relations derived from natural convection heat transfer research along vertical heated plates. Warrionton et al. [6] (1995) carried out experiments in scaled test cell with Trombe wall. The fluid temperature distributions and flow patterns were examined. Awbi and Gan[7] (1992), Gan[8] (1998) and Ziskind et al.[9] (2002) used CFD programs to simulate the airflow and heat transfer in the Trombe wall. It can be found that most of the above researches use CFD technique and the obtained theoretical formulas are complex, which don't help to the engineering calculation. Besides, the numerical model can't describe the real situation thoroughly due to many assumptions in the procedure of resolving the governing equations.

Previous work reveals that there are many parameters and different climatic conditions that affect the thermal performance of the Trombe wall, a full understanding of the heat transfer process is required and the simulation technique of performance of the Trombe wall then can be used properly. Therefore, there is a need to further study the convection heat transfer.

In this study, the experiment of the passive solar building with Trombe wall in north cold climate is carried out. The dominant factor affecting indoor air temperature is analyzed and the natural convection heat transfer process in the channel is investigated. It can provide reference for improving the mathematical model of the natural convection heat transfer.

2. EXPERIMENTAL SETUP

The experiment has been executed in a full scale passive solar house with Trombe wall located at the campus of Dalian University of Technology（N38.54°，E121.38°, Dalian China.The test cell has the size of 3.9m×3.9m×2.8m. Massive wall beside the south window is made of 300mm thick concrete, which has a big thermal storage capacity. The absorptive surface of massive wall is painted dark green. The width of channel is 0.1m and the high of massive wall is 2.1m. The dimensions of the upper/lower vents in massive wall are 150mm× 170mm respectively. The other external walls of the cell consist of 300mm thick cinder block and 100mm thick outside Styrofoam panel. During the test, the vents were opened from 7:30 to 17:30.

The position of the testing points is shown in Fig.1. The temperature of air and surfaces of the building envelope are recorded automatically every 10 minutes and saved in the computer with a data-logger device. The wind velocities of the vents are recorded automatically every 5 minutes by the wind velocity recorder SERIES EE66. Silver paper and thermal insulation materials are used to prevent direct sunshine projecting all probes. Outdoor parameters (such as temperature, relative humidity, wind speed, precipitation and atmospheric pressure) are recorded by WMR968 cable free weather station. Solar radiation intensity is recorded with the PC-2 Pyranometer. The data above are all collected every 10 minutes and the test was performed in Nov. 2004.

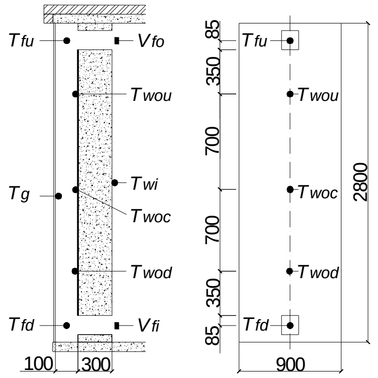

Fig. 1 Position of testing probes in the Trombe wall system

3. RESULTS AND DISCUSSION

3.1 Factors Influencing Indoor Air Temperature

The heat balance equation for the passive solar building is expressed as:

$$A_{wi} h_{wi}(T_{wi} - T_r) + A_f \upsilon_f \rho c(T_{fu} - T_{fd}) + A_g \alpha^D I = A_w k(T_r - T_a) \quad (1)$$

Where, A_{wi} is the inside surface area of massive wall, m^2; A_f is the area of vent, m^2; A_g is the area of direct gain window, m^2; A_w is the area of envelope in solar house, m^2; T_r is the indoor air temperature, ℃; T_{wi} is the inside surface temperature of massive wall, ℃; T_{fu}, T_{fd} is the air temperature of upper and down vent respectively, ℃; T_a is the ambient temperature, ℃; I is the solar radiation intensity of vertical surface, kW/m^2; h_{wi} is the convection heat transfer coefficient between inside surface of massive wall and indoor air, kW/(℃m^2); k is the heat transfer coefficient of envelope in solar house kW/(℃m^2); c is the specific heat of air, kJ/(kg℃); $\rho$is the density of air in channel, kg/m^3; υ_f is the velocity air flow of the vent; α^D is the transmittivity of the glazing. Eq.(1) shows that under the fixed geometrical condition of building, the influencing factors of indoor air temperature in the test cell include the solar radiation intensity I, the inside surface temperature of massive wall T_{wi}, the enthalpy of the air through the upper vent $h_{ou}=\upsilon_f \rho c T_{fu}$ and the ambient temperature T_a.

Fig. 2 shows that the inside surface temperature of massive wall and indoor air temperature have same changing trends and the difference between them is not obvious. Eq.(1) also shows that the convective heat flux of the inside surface of massive wall is small.

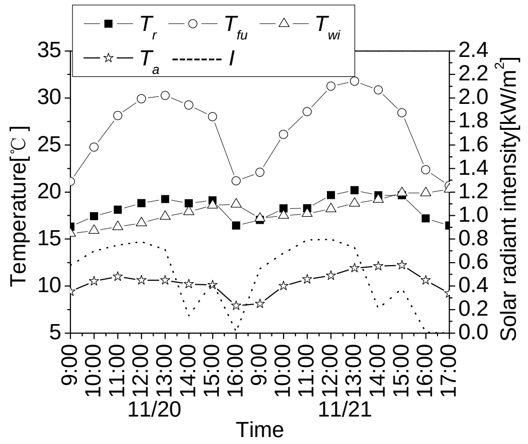

Fig. 2 Daily variation of T_r, T_{fu}, T_{wi} , T_a , I and υ_f

In order to further investigate the dominant influencing factors of indoor air thermo-circulation during the day-time, experimental data from four sunny days are used for stepwise regression to obtain the main influencing factors of T_r. The results are shown in Table 1.

Table 1 shows that T_a is eliminated, and h_{ou}, T_{wi} and I are main influencing factors. Based on partial regression coefficient, the linear correlation decrease in turn with h_{ou}, T_{wi} and I, and the heat transfer through the thermo-circulation is the dominant factor of T_r. The analysis results indicate that the convective heat transfer in the channel is the most effective factor, so enhancing the natural convection through the channel is the key way to improve the thermal efficiency of the passive solar building with Trombe wall.

3.2 Analysis of the Flow Pattern in the Air Channel

In normal thermo-circulation, the air flows from channel to room, so the airflow in the channel can be regarded as natural convective flow between two vertical parallel plates. Providing that the widthδ-to-height H ratio satisfies the following Eq. (2), the channel between two vertical parallel plates can be regarded as "wide channel" and the disturbing effect of the air flow along one plate on the other can be neglected, and this transition criterion can be determined for single vertical plate[10].

$$\delta/H > Ra_H^{-1/4} \quad \text{or} \quad \delta/H > Ra_\delta^{-1} \qquad (2)$$

Where $R_a = g\beta\Delta T\, H^3/(\nu a)$ is the Rayleigh number and the characteristic temperature ΔT is the temperature difference between the absorbing surface or glazing and the air in the channel. Eq.(2) shows that Ra is determined by the characteristic dimension of the height of massive wall H and the width of channelδ. The result shows that as $2.75\times10^{-3} < Ra_H^{-1/4} < 3.6\times10^{-3}$ and $2.75\times10^{-3} < Ra_\delta^{-1} < 3.6\times10^{-3}$, both are far less than the width-to-height rate: $\delta/H = 0.1/2.1 = 0.048$. So the natural convection of channel can be regarded as the problem of single vertical heated plate.

The transition of natural convection is complex and hasn't been solved very well. Since the critical Grashof number (Gr= 4×10^8) of vertical flat observed by the Eckert and Soehnge utilizing interferometer, the problem has been discussed for a long time and the boundary layer of natural convection hasn't been recognized thoroughly. According to the latest experiment result, the Gr should be the criterion to distinguish the flow pattern. It gives more agreement with the experimental result than the recommended $Ra=GrPr$[11]. For a single vertical plate, it is

Tab. 1 Regression coefficient and partial regression coefficient

	Regression coefficient		T	P	Partial correlation coefficient	Collinearity
	B	Standard deviation				
Constant	6.051	0.524	11.557	0.000		
H_{ou}（kW/m^2）	0.191	0.011	17.035	0.000	0.956	1.947
T_{wr} (°C)	0.478	0.033	14.682	0.000	0.943	1.454
I（kW/m^2）	1.249	0.221	5.662	0.000	0.737	1.761

commonly regarded that $Gr\sim10^9$（$10^{-3}\leq Pr\leq10^3$）is the transition criterion as the natural convection flow from laminar to turbulent [12].

Experimental data from four sunny days (11.20, 11.21, 11.27, 11.28) with normal thermo-circulation (9:00-16:00) is utilized. The distributing frequency of *Gr* with time along the height of massive wall is analyzed to identify the flow pattern and the flow process is divided.

Fig. 3 shows the variation of air flow pattern in the channel during the whole thermo-circulation process: (1) Because massive wall is usually at a higher temperature than the glazing, the *Gr* governing the natural convection on massive wall side is always higher than that beside the glazing at the same time with the same height; (2) The air flow on massive wall side are laminar below 0.6m height, turbulent in most time (about 71%) and turbulent above 1m height; (3) The air flow on glazing side are laminar below 0.6m height, laminar in most time (78%) at 0.8m height and turbulent in most time (91%) at 1m height and all the time above 1.4m.

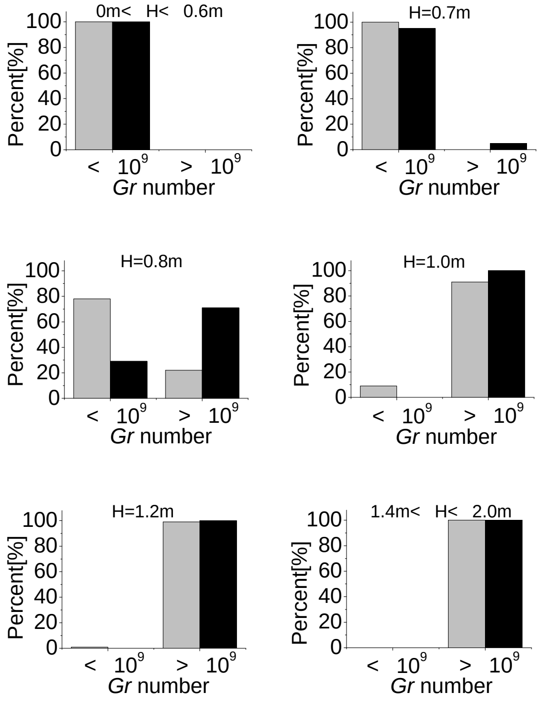

Fig. 3 Time distributing frequency of *Ra* number

（ ▯ Along glazing ■ Along wall）

Fig. 4 shows the variation of *Gr* along the height of the channel at 12:00. *Gr* ranges from 1.69×10^7 to 2.34×10^{10}. The airflow gradually develops from laminar to turbulent. The transition occurs at the height between 0.7m and 0.8m.

The results show that the transition on massive wall side mostly occurs at the height between 0.6m and 0.8m. When the natural convection is relatively weak, the transition occurs at the height between 0.8m and 1m. The transition on glazing side occurs at the height between 0.8m and 1.0m. The airflow of both sides at least half height is turbulent. The airflow in the channel isn't always laminar or turbulent and is a complex flow, with the transition from laminar to turbulent.

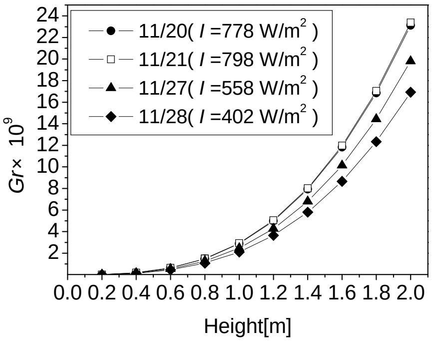

Fig. 4 The variation of *Gr* along the height of massive wall at12:00.

3.3 Heat Transfer Process in the Channel

The experimental data indicate that the experimental correlation of average *Nu* of the air along the channel can be obtained as followings [13]:

$$Nu = 5.86\times10^{-7}\times(Ra)^{0.845} \qquad (3)$$

Fig. 5 shows that the thermo-circulation can be divided into three periods: coast up, maintenance and weaken. During the coast up period, *Nu* is quite small due to the small temperature differences between the air in the channel and the surfaces (absorbing surface and glazing). In sunny days, the coast up period can last for 2.5 hours. In maintenance period, *Nu* keeps steady although the temperature of the surfaces and

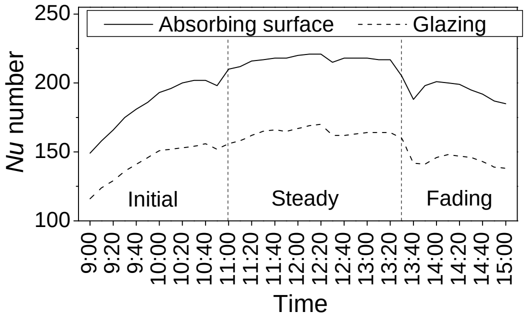

Fig. 5 The variation of *Nu* during the circulation

air change all the time. During the test period, steady normal circulation occurs at about 11:00, and it keeps for 2.5 hours. The third period can last for 3.5 hours.

4. CONCLUSION

In this study, the natural convection characteristics in Trombe wall of the passive solar building are carried out for the first time in China. It provides the reference for further predicting the thermal performance of the passive solar building with Trombe wall. The following conclusions can be obtained:

(1) During the thermo-circulation process, the main factors influencing indoor air temperature are the solar radiation intensity I, the inside surface temperature of massive wall T_{wi}, and the enthalpy of the air through the upper vent $h_{ou}=\upsilon_f \rho c T_{fu}$. However, heat transfer to the room with the thermo-circulation through channel is the dominant factor affecting indoor air temperature. Enhancing the natural convection heat transfer through the channel is the key way to improve the thermal efficiency of the passive solar building with Trombe wall.

(2) In this experiment, the flow pattern of the air in the channel is complex, with the transition from laminar to turbulent, and the airflow is turbulent at least half height of the wall during the positive thermo-circulation.

(3) The day-time thermo-circulation can be broken up into three periods: coast up, maintenance and weaken, and during the maintenance period, the changes of the solar radiation intensity and surface temperatures have little effect on *Nu*.

This experiment is carried out in passive solar house with typical construct and geometry parameters, and the natural convection characteristics under different building structures and dimensions, and insulation levels still need further study.

REFERENCES

[1] Trombe F, et al. Some performance characteristics of the C.N.R.S. solar house collectors. Passive Solar Heating and Cooling Conference Workshop and Proceedings[C]. Albuquerque: New Mexico, 1976.

[2] Hocevar C J. Thermocirculation data and instantaneous efficiencies for Trombe walls. Proceedings of 4th National Passive Solar Conference[C]. Kansas City: Missouri, 1979.

[3] Akbari H and Borgers T R. Free convective laminar flow within the Trombe wall channel [J]. Solar Energy, 1979, 22:165-174.

[4] Borgers T R and Akbari H. Free convective turbulent flow within the Trombe wall channel [J]. Solar Energy，1984，33：253-264.

[5] Smolec W and Thomas A. Theoretical and experimental investigatings of heat transfer in a Trombe wall [J]. Energy Convers. Mgmt., 1993, 34(5): 385-400.

[6] Warrington R O and Ameel T A. Experimental studies of natural convection in partitioned enclosures with a Trombe wall geometry [J]. Journal of Solar Energy Engineering, 1995, 117(1):16-21.

[7] Awbi H B and Gan G. Simulation of solar induced ventilation [J]. Renewable Energy Technology and the Environment, 1992, 4: 2016–2030.

[8] Guohui Gan. A parametric study of Trombe walls for passive cooling of buildings [J]. Energy and Buildings, 1998, 27:37-43.

[9] Ziskind G, Dubovsky V, Letan R. Ventilation by natural convection of a one-storey building [J]. Energy and Buildings, 2002, 34(1): 93–104.

[10] Adrian Bejan．Heat Transfer[M]．New York: John Wiley & Sons Incorporation, 1993.

[11] Shiming Yang, Tao Wenquan. Heat transfer (third edition) [M]. Beijing: higher education publisher, 1998, 178-182.

[12] Buxuan Wang. Heat and mass transfer in engineering [M]. Beijing: science publisher，2002，31-32.

[13] Bin Chen，Peng Sun，Huijuan Chen. Experimental investigation of thermal circulation process of Trombe wall in a full- scale passive solar house. ISES Solar world Congress[C], Orlando: Florida, 2005.