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## Experimental and Numerical Studies of Solar Chimney for Ventilation in Low Energy Buildings

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### Abstract

As an effective way to protect environment and save energy in buildings, passive ventilation method has generated intense interest for improving indoor thermal environment in recent years. Among these passive ventilation solutions, design of solar chimney in buildings is a promising approach for guiding natural ventilation orderly. Many studies about solar chimneys have mainly focused on achieving a better ventilation performance both experimentally and theoretically in ideal condition, whereas experimental studies are mainly focused on small-sized equipment. This research examines the performance of a full-scale solar chimney in a real building in East-ern China. The measured performance is compared with theoretical calculation and numerical simulation. In a solar chimney of 6.2m length, 2.8m width and 0.35m air gap, the experimental results show that air flow rate of 70.6 m<sup>3</sup>/h~1887.6 m<sup>3</sup>/h can be achieved during the daytime in the testing day. Comparing measured value with theoretical value, the flow rate is generally lower than the theoretical value. By data analysis, the suggested discharge coefficient Cd of solar energy in real engineering project is 0.51. With the use of this suggested value, the simulation results show that during the transition seasons (from April to October), solar chimney can be used for saving energy with an energy saving rate around 14.5% in Shanghai. It is shown solar chimney is an effective approach to save energy for residential buildings in transition seasons in hot summer and cold winter area in China.

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*Keywords:* Solar chimney; Natural ventilation; Field measurement; Simulation

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## 1. Introduction

Nowadays, referring to the increasing rate of environmental pollution and limitation on fossil fuels, the use of sustainable energies becomes to be inevitable for the world[8]. Natural ventilation technology has attracted much attention because it can effectively improve the thermal environment of buildings. Natural ventilation can be generally divided into two types: organized natural ventilation and unorganized natural ventilation. Organized natural ventilation is realized in the form of exhaust equipment in the building channels through which indoor air is discharged to the outside. It can effectively control the air flow. Unorganized ventilation is realized by the means of leaks and cracks in structures (air infiltration), and by airing the room through the open windows and vents. As a kind of organized natural ventilation technology, solar chimney has attracted attention in recent years because of its ability to effectively drive natural ventilation.

The method of using solar radiation to enhance natural ventilation appeared in the 16th century in Italy. It is known as "Scirocco rooms"[11]. In recent years, scholars have made researches on theoretical models, numerical simulation and experiments of solar chimney [13]. On the aspect of theoretical research, Bansal et al. set up a steady-state mathematical of solar chimney in 1993[9]. Anderson et al. used 0.57 as the discharge co-efficient for a sharp-edged opening [6]. Flourentzou et al. [3] discussed the value of velocity coefficient, contraction coefficient, and discharge coefficient by using gas tracer method. The value of discharge coefficient was suggested as  $0.6 \pm 0.1$ . Ong established one-dimensional steady state mathematical model to calculate air temperature in the air channel in 2003 [5]. J. Arce used 0.52 as the discharge coefficient for it's closer to the real situation in experiments [9]. On the aspect of experimental investigations, Bouchair obtained an aspect ratio (Height / depth) for the optimal ventilation performance of a solar chimney [1]. Angui Li et al. discussed the temperature and air velocity distribution in a solar chimney based on the research of a vertical solar chimney. It was pointed out that the temperature and velocity boundary layer formed near the heated surface [2]. Chen et al. pointed out that the theoretical result was usually higher than measured value due to underestimation of inlet and outlet losses [5]. At present the calculation of solar chimney's flow rate mainly bases on the ideal experimental situation, while the flow rate may be lower than the existing theoretical model value considering all kinds of resistance in a real building. Based on a real solar chimney in the P+ demonstration building in Changzhou, this article discusses the value of discharge coefficient and simulates the energy-saving efficiency when a solar chimney is used in Shanghai.

## 2. The Ventilation Effects of the Solar Chimney

### 2.1. Theoretical model

Figure 1 shows the basic form of the solar chimney discussed here. The solar chimney is consist of a glass plate, a dark heat absorbing plate, a layer of thermal-protective material, a metal support, a metal blind flange, air inlets and air outlets. The ventilating duct is between the glass plate and the heat absorbing plate.

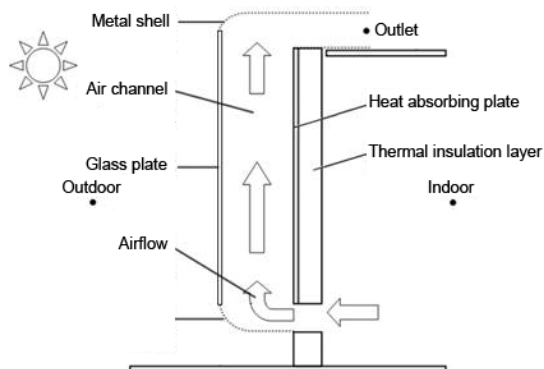


Fig.1. The sketch of a solar chimney

When the solar radiation through the glass plate is absorbed by the heat absorbing plate and the chimney channels, the temperature of the air in the ventilating duct will rise and produce the heat pressing difference, which can help the air flow. The amount of ventilation produced by the solar chimney is expressed by Equation 1 (Bansal et al. 2005), where  $Q$  is the air flow rate in chimney,  $C_d$  is the coefficient of discharge,  $A_o$  is the cross-sectional area of outlet to airflow channel,  $\Delta T$  is the air temperature difference between inlet and outlet,  $L$  is the stack height,  $T_{f,i}$  refers to air temperature at inlet of channel, and  $A_r$  refers to ratio of cross-sectional area of outlet to that of inlet.

$$Q = C_d A_o \sqrt{\frac{2g\Delta TL}{T_{f,i}(1+A_r^2)}} \quad (1)$$

The discharge coefficient  $C_d$  can be expressed by Equation 2 (Flourentzou et al. 1998), where  $C_v$  refers to velocity coefficient,  $C_c$  refers to contraction coefficient, and  $\zeta$  refers to the resistance coefficient.

$$C_d = C_v C_c = \frac{C_c}{\sqrt{1+\zeta}} \quad (2)$$

The value of  $C_d$  is usually decided by experience. K.T.Anderson (Anderson 1995) suggested that for a rectangular thin-walled opening, the value of  $C_c$  is usually between 0.02 and 0.1. Choosing the upper limit, then the value of  $C_c$  is 0.6 and the value of the flow coefficient  $C_d$  is 0.57. Shiv Lal (Lal et al. 2016) gave the ideas that  $C_d$ 's value is more close to 0.65–0.7 for tall solar chimney with smooth materials. In practical construction, the value of  $C_c$  and  $C_v$  is different for the distinction of the materials, the structures and the forms used by the solar chimney.

## 2.2. Experimental test

In this experiment, the value of  $C_d$  is experimentally determined by measuring air velocity, the inlet and outlet areas, the solar radiation, the chimney's height and the indoor air temperature. The experiment measurements were carried out in the P+ demonstration building (Figure 2 and Figure 3) in Changzhou, China. In the ground floor, there is an air inlet set on the top of the wall, meanwhile the air outlet is set on the roof.



Fig.2. solar chimney in P+ building

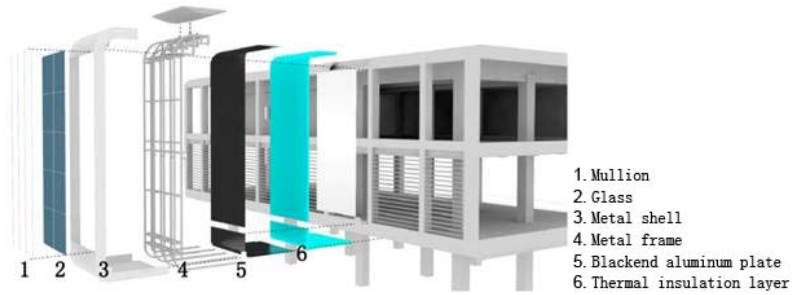


Fig.3. solar chimney’s decomposition

The data was collected in windless or weak-wind days. The anemograph was set in the air inlet. At the same time, we set solar radiation table on the surface of the chimney. Besides, we also measured air temperature inside and outside the building. Parameters measured in this experiment contained: air temperature inside and outside the building (°C), incident solar radiation on south facing vertical surface (W/m<sup>2</sup>), the velocity of air flow in tunnel and around the inlet as well as the outlet. Instruments used in the experiment contained: solar radiation table (Type:JTR05), hot wire anemometer (Type:Testo425,AVM-01,ST732), air thermometer (Type:TES1360A), temperature recorder (Type:H08-004-02).

Results show that from 9:15 to 13:15, the incident solar radiation on the south facade is ranging from 5W/m<sup>2</sup> to 600W/m<sup>2</sup>, The ventilation velocity in air channel is ranging from 0.02m/s to 0.45m/s. With the increasing of solar radiation, the amount of ventilation produced by solar chimney also rises. Fitting the remaining valid data, the discharge coefficient *C<sub>d</sub>* of 0.51 can be determined (Figure 4). We can find that the calculated value from N.K.Bansal's mathematical model appears to be higher than the value determined during experiments, which may result from the underestimation of the practical resistance of solar chimney. The resistance a solar chimney may face with is usually more serious for its large shape, the excessive wind speed and materials the solar chimney uses, that is why the solar chimney usually behaves better under the theoretical calculation.

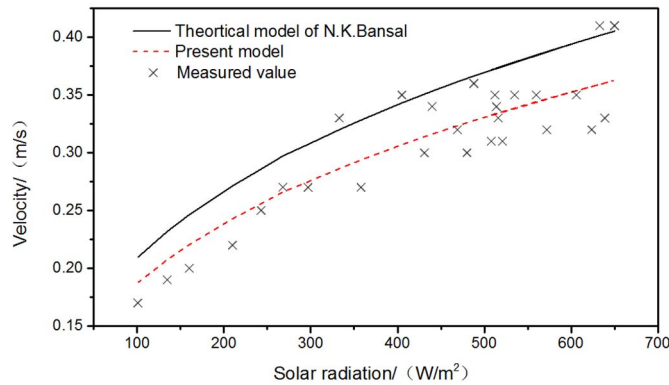


Fig.4. Comparison diagram of N.K.Bansal theoretical model, measured value and the present model

Table 1. An example of a table.

An example of a column heading	Column A ( <i>t</i> )	Column B ( <i>t</i> )
And an entry	1	2
And another entry	3	4
And another entry	5	6

2.3. Numerical simulation

Numerical simulations are based on the following simplifications and assumptions (Wang 2003):(1) Stable indoor and outdoor environment; (2) Gas flow in solar chimney air channel is turbulent flow; (3) Internal flow of gas is Newtonian fluid and incompressible flow; (4) Heat transfer process does not take into account inside the chimney; (5) Ignoring air infiltration; (6) Assuming that material properties are independent of temperature; (7) Gas in the channel conforms to the Boussinesq assumption. Using a Realizable k-ε turbulence model and an enhanced wall function method (Liu 2012) and subdividing the mesh at the near wall part of the solar chimney air channel. The inlet boundary conditions are: 0Pa, 298K; the outlet boundary condition is: 0Pa, 295K. DO model (Liu 2012) is selected in this simulation and the internal wall emissivity is set to 0.95.

By selecting the cross section of the solar chimney channel at a height of 1.5m, the numerical simulation results of the ventilation rate are compared with the experimental results, which is shown in the Table 1. It can be seen that the numerical simulation is in a good agreement with the experimental results. By selecting the vertical section of the chimney channel, the comparison between numerical analysis and the experimental results of the ventilation rate is shown in figure 5.

Table 1. Comparison between numerical analysis and actual measurement

Solar radiation on vertical plane (W/m <sup>2</sup> )	101	160	268	358	405	469	516	560	600
Numerical simulation wind speed (m/s)	0.184	0.217	0.257	0.288	0.300	0.316	0.327	0.336	0.345
Wind speed of experiment results (m/s)	0.17	0.2	0.27	0.27	0.35	0.32	0.33	0.35	0.35

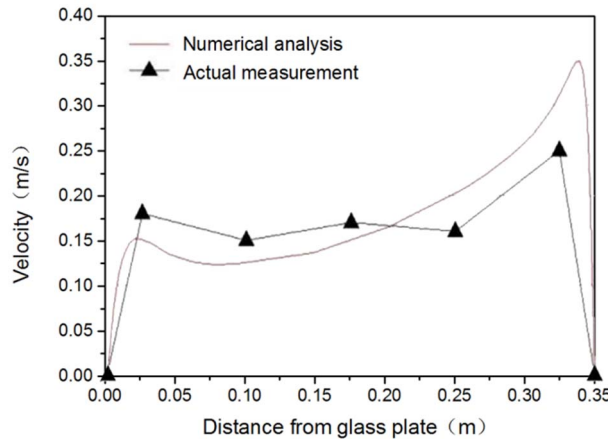


Fig.5. Comparison between numerical analysis and actual measurement (vertical solar radiation is 100W/m<sup>2</sup>)

It can be seen from Figure 5 that the wind speed of the vertical section in the solar chimney's channel has a great change near the wall, and a gentle change at the center of the channel. This is because the gas in the air channel is affected by the viscous resistance of the wall, and finally the near-wall layer forms (Li et al. 2009).

3. Energy Simulation

3.1. Simulation description

A numerical model of the P+ demonstration building with the solar chimney was established in EnergyPlus software. The room where the solar chimney works is 117 square meters in area. The numerical simulation is based on the following assumptions: (1). The air temperature is same in the same thermal environment; (2). The inside

surface temperature is the same and the heat transfer process is one-dimensional; (3). The "Civil Building Hot and Humid Evaluation Criteria" suggests  $18^{\circ}\text{C} \sim 28^{\circ}\text{C}$  as the acceptable temperature range for the indoor thermal comfort, the ideal air conditioning system starts running automatically when the temperature is lower than  $18^{\circ}\text{C}$  or higher than  $28^{\circ}\text{C}$ ; (4). According to the "Office Building Design Specification JGJ 67-89", the average fresh air volume indoor must be of  $30\text{m}^3/\text{h}$  per person; (5). Discharge coefficient of the solar chimney is set to 0.51; (6). Per capita area of  $8\text{m}^2$ , lighting power density of  $12\text{W}/\text{m}^2$ , electrical power density of  $15\text{W}/\text{m}^2$  has been set. Simulation is based on the typical meteorological conditions in Shanghai.

### 3.2. Simulation result

Under the typical meteorological condition of Shanghai, ventilation volume produced by the solar chimney in the case building per month is shown in Figure 6.. In order to verify the accuracy of this numerical simulation, a random day (September 1st) is selected to calculate the ventilation generated by the solar chimney according to meteorological parameters and theoretical model. And the calculated result is compared with the simulated one from EnergyPlus, which is shown in Figure 7.

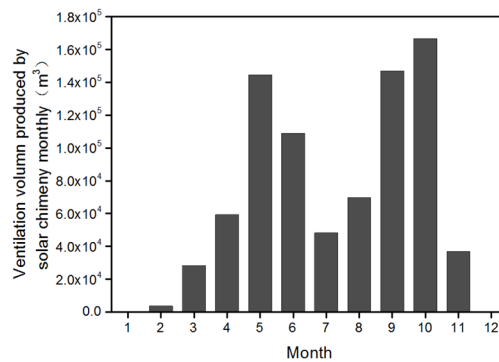


Fig 6. hourly ventilation volume produced by the solar chimney (m<sup>3</sup>/s)

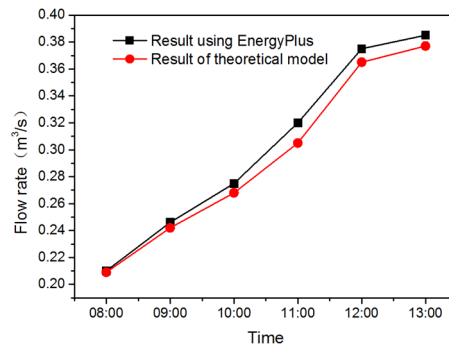


Fig 7. the comparison of calculated result with the simulated one on Sep.1

Under the the control conditions above , April to October is suitable to use solar chimney. Under typical weather condition in Shanghai, the maximum ventilation can reach  $0.467\text{m}^3/\text{s}$ ; the cumulative annual ventilation can reach  $813092.7\text{m}^3$ . Figure 7 compares the simulation results from Energyplus on September 1 with the theoretical calculation of the solar chimney ventilation. The result shows a good agreement, indicating the accuracy of the using EnergyPlus software.

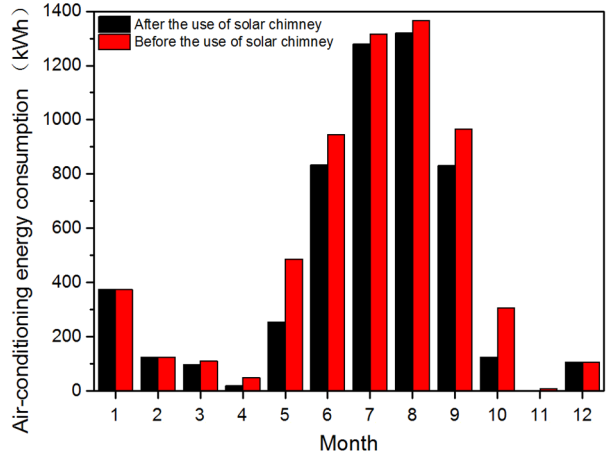


Fig 8. The air conditioning energy consumption simulation of the office space before and after the use of solar chimney

Table 2. Energy saving rate after using solar chimney

Time period	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	All year
Energy saving rate	61.8%	47.7%	11.8%	2.8%	3.4%	13.9%	59.6%	12.9%

Figure 8 shows the comparison of the energy consumption of air conditioner when solar chimney is on and off. With the use of solar chimney in air-conditioner's refrigerating season (April to October), the energy-saving rate is shown in Table 2. It can be seen from the chart that in Shanghai, solar chimney has a significant energy-saving effect, with energy-saving efficiency of 14.5% in air-conditioner's refrigerating season or 12.9% annually. According to the monthly air conditioning consumption, solar chimney has a certain effect in air-conditioner's refrigerating season (April ~ October). What's more, the energy-saving rate reaches 61.8%, 47.7%, 11.8%, 13.9% and 59.6% respectively in the transitional season (April, May, June, September and October). Solar chimney achieves an optimal energy-saving effect in May, June, September, October, and the energy consumption saved in these months respectively reached 232.2kWh, 111.6kWh, 134.1kWh, 182.kWh.

**4. Conclusion**

Based on the measurement of a solar chimney in the P+ demonstration building in Changzhou, China, solar radiation measured ranges from 5W/m2 to 600W/m2 and the measured velocity ranges from 0.02m/s to 0.45m/s in the testing day. With the calculation of the measured result and the theoretical result, the discharge coefficient of 0.51 is suggested in a real engineering project. The excessive wind speed and materials a solar chimney use may enhance the resistance the solar chimney faces with. This finally leads to the decrease of the flow rate. Results show a good agreement between numerical simulation and measured performance. Compared to the numerical simulation result, the measured value fluctuates. This may be influenced by various forms of resistance, including the resistance on the air channel wall surface, metal frame, air inlet and outlet.

The energy simulation result shows that solar chimney has a good energy-saving effect. For example, under the typical weather condition in Shanghai, with the use of a solar chimney in this study case, the energy-saving efficiency can reach 12.9% annually and 14.5% during the air-conditioner's refrigerating season. Solar chimney works well particularly in the transition season. This is because during the transition season, solar chimney can be opened longer as the outdoor air temperature is appropriate for longer periods of time, which leads to more natural ventilation and more energy-saving.



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