

Impact of non-uniform heat flux on ventilation performance of solar chimney

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Abstract. Solar chimney (SC) is an effectively practical way to enhance building natural ventilation through thermal buoyancy force, which is induced due to the temperature difference between indoor and outdoor air temperatures. The ventilation performance of solar chimney directly depends on the heat flux distributions and values in the absorbed plate. Recently, many researches have been done on the thermal performance of solar chimneys under uniform heat flux. However, the uniform heat flow distribution cannot reflect the uneven characteristics of the solar radiation. There are few studies focused on the flow characteristic and thermal performance of solar chimneys under non-uniform heat flux distributions. In this paper, a two-dimensional numerical model of solar chimney integrated building is firstly established to explore the natural ventilation performance under non-uniform heat flux distributions. The numerical simulation is conducted to predict the flow and heat transfer characteristics in the room as well as in solar chimney. Subsequently, the effects of the location of the vent are analyzed to evaluate the performance of the solar chimney system. Finally, a comparison between the ventilation performance of solar chimney under the uniform heat flux and the non-uniform heat flux distributions is presented, and the thermal and flow structures of the solar chimney integrated building are further illustrated simultaneously. Research results show that the ventilation performance of solar chimney is closely related to its heat flux distribution, and the inhomogeneity of the heat flux of solar chimney will decrease the ventilation performance of the building. In addition, the position of the vent have highly influence on the flow structure and thermal performance for the solar chimney as well as the building. This paper will provide theoretical basis and technical approach for the improvement of the performance of the solar chimney, especially for the non-uniform heat flux distribution.

1 Introduction

Since the COVID-19 outbreak in 2019, people have been spending less time outdoors to reduce the spread of the virus and deaths from infection. Staying in an unventilated room for a long time causes the air with a large amount of harmful ingredients that cannot be discharged outdoors, which make people more susceptible to infection with virus. Therefore, it is necessary to develop indoor ventilation techniques [1] to improve indoor air quality and take step forward in the battle against airborne virus transmission. As a natural ventilation device with low energy consumption, solar chimney has attracted attention intensively from domestic and foreign scholars [2-4]. The optimization of the solar chimney presents one of the important researches for indoor air quality.

Ramadan et al. [5] carried out a study on the indoor natural ventilation performance of solar chimney. It was confirmed that the increase of the air inlet height can improve the air changes per hour (ACH) of solar chimney. Mathur et al. [6] simulated the ventilation performance of roof solar chimney buildings under the

uniform heat flux. It was found that the ventilation performance of SC reached the maximum value when the chimney tilt angle was 45°. The experimental data for the validation of this study was obtained initially by Shi et al. [7] in a stable indoor environment. It was observed that the inlet height and cavity area play major role to enhance the ventilation of solar chimney. Gan et al. [8] performed the numerical investigation on the influence of aspect ratio of solar chimney on the ventilation. It was reported that the ventilation of solar chimney improved with the increase of the aspect ratio of solar chimney. Jing et al. [9] experimentally investigated that the ventilation performance of solar chimney is optimal when the aspect ratio is 0.5. Khanal et al. [10] proposed that the ventilation capacity of solar chimney can be enhanced by adjusting tilt angle through experimental methods.

The above studies show that the solar chimney structure can heavily affect the ventilation performance of SC buildings under uniform heat flux. Most of the previous studies focus on the performance of solar chimney under the condition of uniform heat flux. However, the ventilation performance of the solar

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chimney under the non-uniform heat flux is poorly analysed. It cannot reflect the uneven distribution of solar radiation in the SC buildings due to shielding and solar incident angle. Hence, it is essential to investigate the influence of non-uniform heat flux on the ventilation performance of solar chimney.

2 Numerical model

The two-dimensional physical model of the vertical solar chimney (SC) attached to the cavity is depicted in Fig.1. The solar chimney consists of an air channel enclosed by a glass cover and an absorbed plate, which is connected with the vented room by the air inlet. For the convenience of calculating the fluid in the cavity, the following assumptions are adopted to enable solving the mathematical model:

- Flow through chimney is considered: laminar and steady-state;
- The air of the chimney channel is assumed to be incompressible.
- The inlet air temperature of the chimney is equal to the indoor temperature;
- The influence of buoyancy is only considered, and the friction loss caused by flow is ignored.

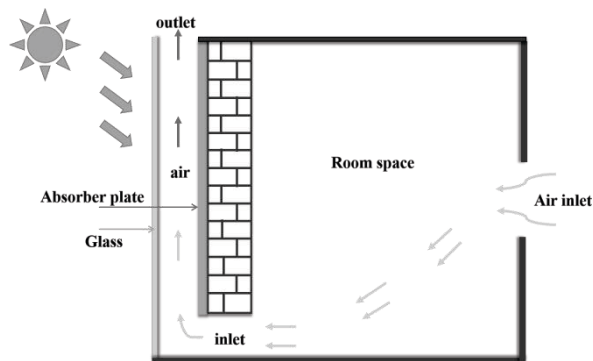


Fig. 1. The physical model of solar chimney buildings.

2.1 Numerical analysis and geometric model

The entire domain is wide $W = 1$ m \times height $H = 1$ m, with an attached chimney of aspect ratio $d/H = 0.1$, and $b/W = 0.1$. Furthermore, the cavity considers having an open side-window (height, $H_w = 0.3$ m) at middle wall. The fluid and heat transfer within the SC and room is assumed to be governed by the 2D Navier-Stokes equations together with the energy equation. The fluid is incompressible and satisfies the Boussinesq approximation which implies that the variation of density with temperature is negligible. Here, the governing equations are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty) \quad (2)$$

$$\rho C_p (u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}) = k \frac{\partial^2 T}{\partial y^2} \quad (3)$$

Where g is gravitational acceleration (m/s^2), k is thermal conductivity ($W/(m \cdot K)$), u, v is air velocity in the x and y direction, respectively (m/s), β is Coefficient of thermal expansion ($1/K$), ν is kinematic viscosity (m^2/s).

In natural ventilation, ACH is important for evaluating the performance of solar ventilation, which is the ratio of the air volume flow rate to the room volume. This index is defined by ASHRAE as

$$ACH = \frac{\dot{V} \times 3600}{V} \quad (4)$$

In this study the room total volume (V) is considered 27 m^3 to simulate an actual room size for the purpose of reasoning values and to compare with published data in ref. [11]. \dot{V} is ventilation rate (m^3/s). Furthermore, it should be noted that the room model volume could be used to obtain ACH.

3 Model Validation

Under uniform heat flux, a comparison between the obtained results and the numerical analysis of Ramadan et al. [5] and experimental results of Mathur et al. [11] is shown in Fig. 2. There is a fluctuation of both theoretical results around the measured experimental data. However, the error between experimental results and simulation results is about 5% due to the thermal radiation loss in the experimental process. Therefore, the results of error analysis demonstrate the feasibility of the numerical model.

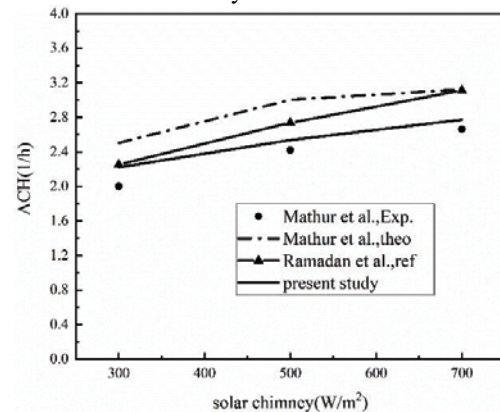


Fig. 2. Comparing with numerical analysis and experimental published data.

4 Results and discussions

4.1 The influence of Gaussian distribution

To investigate the influence of Gaussian heat flux distribution, the variation of average outlet velocities at different solar intensities is compared with uniform heat flux distribution results. Fig. 3 shows the outlet velocity and ACH profile across the chimney channel with a width of 0.1 m under Gaussian heat flux distribution. Fig. 3 (a) illustrates heat flux distribution of the absorbed plate when the solar intensity is 300 W/m^2 . In this figure, the solar intensity on the absorbed plate shows a Gaussian distribution along the

height of the absorbed plate. In Fig. 3 (b), the outlet velocity and ACH variation are depicted at the location of $b/H = 0.1$ under various solar intensities. The average outlet velocity and ACH gradually increase as the solar intensity increases, with an approximate linear increase in outlet velocity. Besides, non-uniform heat flux leads to a relative low outlet velocity of solar chimney compared to that of uniform heat flux distribution. For any solar intensity, the outlet velocity of the solar chimney has a significant drop for the uniform heat flux distribution. As the heat flux presents Gaussian distribution, the outlet air velocity of the solar chimney decreases by about 19%. This is due to reducing the solar intensity between the two sides of the absorbed plate and the sunlight decreased temperature difference on both sides of solar chimney.

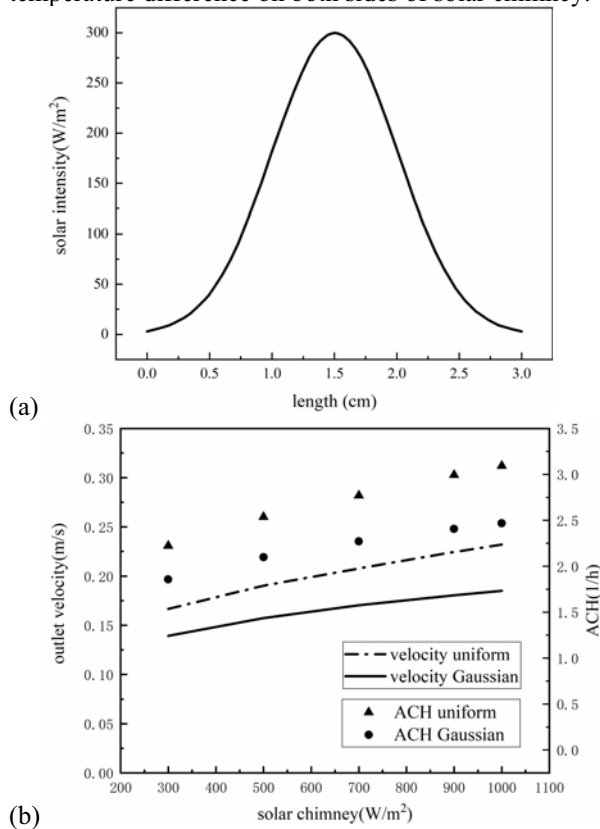


Fig. 3. Analysis diagram of solar chimney performance under Gaussian distribution.

4.2 The influence of Segmented distribution

Considering the sun is blocked by the building, the glass cover can only receive a part of the sunlight, which makes the heat flux on the glass cover and the absorbed plate appear segmented. Fig. 4 (a) describes the heat flux distribution at different positions of the absorbed plate. It is seen that the heat flux distribution on the absorbed plate appears as a segmented function with increasing length. Fig. 4 (b) shows that the comparison of the variation of ventilation performance of solar chimney under different heat flux conditions at a certain inlet size and at different solar intensities. The figure illustrates that with the increase of solar radiation intensity, the outlet average velocity and ACH show a linear increase. For a certain intensity, the

average outlet velocity and ACH of solar chimney is relatively small under Segmented heat flux. The outlet air average velocity of solar chimney decreases about 15% compares with the uniform heat flux because the uneven distribution of solar intensity on the absorbed plate causes the decrease of total solar intensity.

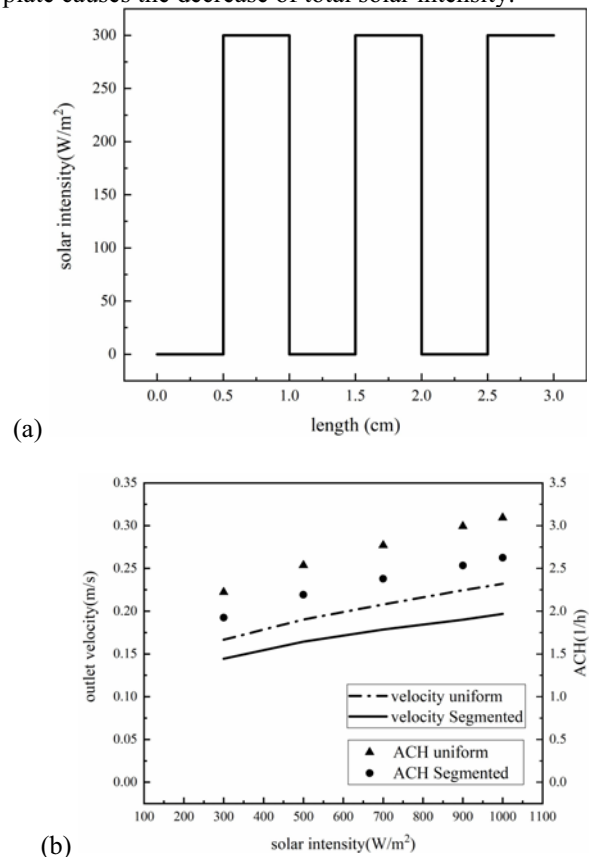


Fig. 4. Analysis diagram of solar chimney performance under Segmented distribution.

4.3 The influence of inlet position

Three inlet positions of cavity are considered: vent-top, vent-mid and vent-bottom. The effect of the inlet position of the cavity on the ventilation performance of the solar chimney at $H_w = 0.3$ m is investigated under Gaussian heat flux at different solar intensities. Fig. 5 shows the flow pattern and zones of separation as a result of varying the inlet position. Since the window height is kept constant, the change of inlet position results in a different number of areas of noticeable flow separation region at the lower part of the chimney as shown in the figure. Table 1 summarizes a quantitative comparison for the air outlet velocity and ACH through the chimney at a certain solar intensity at different inlet locations. The results in the table show that the outlet velocity and ACH of the solar chimney at vent-mid increases by about 10% compared with the others at different solar intensities, and the ACH increases with the increase of the solar intensity.

5 Conclusions

The purpose of this study is to predict the ventilation performance of the solar chimney in terms of ACH as

well as understanding the flow state. The effects of the heat flux distribution and the inlet position of cavity on the performance of solar chimney used for natural ventilation are investigated. Based on the results obtained, the following conclusions can be drawn:

(1) The ACH of solar chimney decreased by about 19% under Gaussian heat flux, and 15% under Segmented heat flux compared with uniform heat flux.

(2) A distinct effect of the vent position on the space flow pattern is found to insuring an optimum position at vent-mid under Gaussian heat flux distribution. The outlet velocity of SC at vent-mid shows an increase nearly 10% compared with the others.

(3) Under any heat flux distribution, the ventilation performance of solar chimney increases with the increases of solar intensities from 300 to 1000W/m².

Table 1. Summary of some result for comparison with vent position

	vent-position	vent-top	vent-mid	vent-bottom
300	v (m/s)	0.137	0.139	0.137
	ACH (1/h)	1.827	1.853	1.827
500	v (m/s)	0.154	0.157	0.155
	ACH (1/h)	2.053	2.093	2.067
700	v (m/s)	0.167	0.170	0.168
	ACH (1/h)	2.227	2.267	2.240

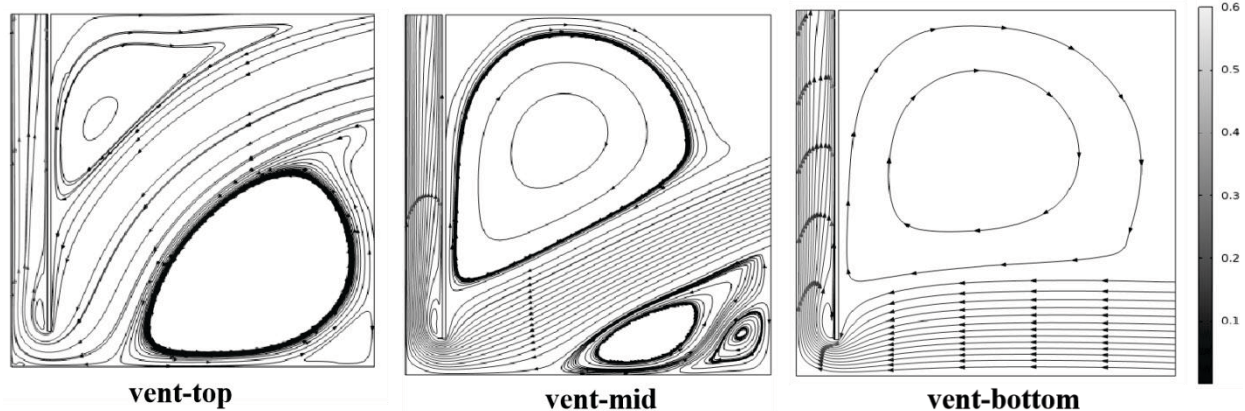


Fig. 5. The cavity flow pattern variation for different vent position.

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