The effects of opening areas on solar chimney performance

L S Ling¹, M M Rahman¹, C M Chu¹, M S bin Misaran¹ and F M Tamiri¹

¹Material and Mineral Research Unit (MMRU), Universiti Malaysia Sabah, Kota Kinabalu, Sabah, Malaysia.

E-mail: mizanur@ums.edu.my

Abstract. To enhance natural ventilation at day time, solar chimney is one of the suitable options for topical country like Malaysia. Solar chimney creates air flow due to stack effect caused by temperature difference between ambient and inside wall. In the solar chimney, solar energy is harvested by the inner wall that cause temperature rise compare to ambient. Therefore, the efficiency of the solar chimney depends on the availability of solar energy as well as the solar intensity. In addition, it is very hard to get good ventilation at night time by using a solar chimney. To overcome this problem one of the suitable valid option is to integrate solar chimney with turbine ventilator. A new type of solar chimney is designed and fluid flow analyzed with the computational fluid dynamics (CFD) software. The aim of CFD and theoretical study are to investigate the effect of opening areas on modified solar chimney performance. The inlet and outlet area of solar chimney are varied from 0.0224m² to 0.6m² and 0.1m² to 0.14m² respectively based on the changes of inclination angle and gap between inner and outer wall. In the CFD study the constant heat flux is considered as 500W/m². CFD result shows that there is no significant relation between opening areas and the air flow rate through solar chimney but the ratio between inlet and outlet is significant on flow performance. If the area ratio between inlet and outlet are equal to two or larger, the performance of the solar chimney is better than the solar chimney with ratio lesser than two. The solar chimney performance does not effect if the area ratio between inlet and outlet varies from 1 to 2. This result will be useful for design and verification of actual solar chimney performance.

1. Introduction

Malaysia is situated at the equatorial region therefore received high solar radiation intensity as well as high relative humidity. This hot and humid climate has posed difficulties in achieving indoor thermal comfort. As a result, the household sector in Malaysia has consumed high electricity mainly for cooling [1].

Solar chimney seems to be a good potential energy conservation strategy to reduce the room temperature. Significant numbers of studies have been done to increase its capability of reducing heat from the room as well as enhanced the rate of natural ventilation [2]. Moreover, solar chimney received energy mainly from the sun which is abundant in Malaysia. The daily average solar radiation received in Malaysia is about 4000 – 5000Wh/m² and average sunshine duration of 4 – 8 hours per day [3].

The design of solar chimney is very simple which consists of glazing, air gap, absorber surface, and insulator. In the solar chimney, energy is harvested through the absorber surface and heating up the air presents between the glazing and the absorber. As a result, the air become lighter and pushed up. The
hot and light air is delivered out from the chimney due to buoyancy force that is known as stack effect. The hot air delivered outside and relatively cold air enters from the room to fill the gap. The process continues as long as the energy is available in the absorber [4]. In order to ensure suitable and reliable ventilation during overcast condition as well as night time, solar chimney integrated with turbine ventilator is one of the good options. This option is suitable as availability of solar and/or wind energy at a reasonable intensity during a large part of any day [5]. Furthermore, this integration system is expecting to further enhance the natural ventilation performance compare to individual system.

In this study, a new type solar chimney is introduced that can be easily integrated with the turbine ventilator. In order to optimize the performance of solar chimney, it is important to understand the effect of different solar chimney’s parameters. The predominant parameters are chimney aspect ratio (stack height/air gap depth), ventilation height (height between inlet and outlet), thermal characteristics of the absorber, and chimney inclination angle [6]. In addition, opening areas of solar chimney have direct and great influence on the air flow rate. The opening areas change the resistance to the flow at inlet and outlet of the chimney [7-8]. Although opening areas have impacts on the performance of solar chimney, but not much investigations have reported on it. Therefore, the aim of this study is to investigate the effect of opening areas on the modified solar chimney performance.

2. Description of analysed solar chimney
The new type solar chimney consists of outer part and inner part. As shown in figure 1, two sides of the outer part are covered by transparent glasses that act as glazing. The glazing allows solar radiation to pass through and the energy is received by the absorber at the inner part.

According to figure 2, two sides of the inner part are absorber and the other two sides are perforated plates. The perforated plates allow air to flow through the chimney. By assembling outer part and inner part together, the new type solar chimney along with its section view is shown in figure 3.

![Figure 1. Outer part of solar chimney.](image1)

![Figure 2. Inner part of solar chimney.](image2)

![Figure 3. Solar chimney and its section view.](image3)
There are 16 different configurations to investigate the effect of opening areas on the performance of a solar chimney as shown in table 1. The inlet and outlet area of solar chimney are varied from 0.0224m² to 0.6m² and 0.1m² to 0.14m² respectively based on the changes of inclination angle and gap between inner and outer wall.

Table 1. Opening areas of the 16 configurations of the solar chimney.

| Outlet area (m²) | Inlet area (m²) | Ratio = \( \frac{Outlet}{Inlet} \) |
|-----------------|----------------|-------------------------------|
| 0.104           | 0.056          | 0.54                          |
| 0.104           | 0.169          | 1.62                          |
| 0.104           | 0.347          | 3.34                          |
| 0.104           | 0.597          | 5.74                          |
| 0.115           | 0.045          | 0.39                          |
| 0.115           | 0.151          | 1.31                          |
| 0.115           | 0.322          | 2.80                          |
| 0.115           | 0.565          | 4.90                          |
| 0.126           | 0.034          | 0.27                          |
| 0.126           | 0.133          | 1.05                          |
| 0.126           | 0.297          | 2.35                          |
| 0.126           | 0.532          | 4.21                          |
| 0.138           | 0.022          | 0.16                          |
| 0.138           | 0.115          | 0.83                          |
| 0.138           | 0.272          | 1.97                          |
| 0.138           | 0.500          | 3.63                          |

3. Modelling the solar chimney

Two approaches are taken to investigate the effect of opening areas on the performance of solar chimney. One of the approaches is via computational fluid dynamics (CFD) software named SolidWorks. Another approach is using the mathematical equations that had been developed by the Xu and Liu [9].

3.1. Computational Fluid Dynamics (CFD)

The following simplifying assumptions are made in modelling the solar chimney with CFD software named SolidWorks:

- Air is considered as flowing fluid
- The air follows the ideal gas law
- Wind effect is not included
- The entire system is at steady state condition
- Frictional losses is negligible due to the very low order of flow velocity
- Air leakage is negligible
- The solar chimney walls are considered as adiabatic wall
- The absorber is considered as pure black body

In this study, the solar chimney modeling has been done under constant heat flux. Assume that absorber acts as heating source and supplied heat energy at constant rate 500W/m². The initial temperature of the whole model has been set to be the same as the ambient temperature at 301K including the solar chimney surface temperature. At the inlet and outlet, the pressure has been considered as ambient which is 101kPa.
The flow in the solar chimney has been simulated at steady state condition. Half of the chimney is considered as computational domain since other part of the chimney is symmetric. The details about the number of mesh have shown in Table 2. Under the similar heating and initial condition setting, different configurations are compared by determining the air flow rate that can be achieved by each configuration.

**Table 2.** Number of mesh cells for different configurations of solar chimney.

| Outlet area (m²) | Inlet area (m²) | Number of cells |
|-----------------|-----------------|-----------------|
|                 |                 | X   | Y   | Z   |
| 0.104           | 0.056           | 14  | 56  | 28  |
| 0.169           | 0.090           | 16  | 46  | 32  |
| 0.347           | 0.173           | 16  | 38  | 32  |
| 0.597           | 0.298           | 16  | 32  | 32  |
| 0.115           | 0.058           | 14  | 56  | 28  |
| 0.151           | 0.077           | 16  | 46  | 32  |
| 0.322           | 0.161           | 16  | 38  | 32  |
| 0.565           | 0.283           | 16  | 32  | 32  |
| 0.126           | 0.063           | 14  | 56  | 28  |
| 0.133           | 0.077           | 16  | 46  | 32  |
| 0.297           | 0.149           | 16  | 38  | 32  |
| 0.532           | 0.266           | 16  | 32  | 32  |
| 0.138           | 0.069           | 14  | 56  | 28  |
| 0.115           | 0.077           | 16  | 46  | 32  |
| 0.272           | 0.134           | 16  | 38  | 32  |
| 0.500           | 0.250           | 16  | 32  | 32  |

3.2. Theoretical calculation

According to Xu and Liu [9], the theoretical mass flow rate ($\dot{m}$), volumetric flow rate ($\dot{V}$), and air velocity ($v$) inside the solar chimney can be estimated through the following equations.

\[
\dot{m} = c_d \rho_f A_0 \left[ \frac{2gL_s \sin \theta (T_f - T_r)}{(1 + A_r^2)T_r} \right]^{\frac{1}{2}} \tag{1}
\]

\[
\dot{V} = \frac{\dot{m}}{\rho_f A_0} = c_d A_0 \left[ \frac{2gL_s \sin \theta (T_f - T_r)}{(1 + A_r^2)T_r} \right]^{\frac{1}{2}} \tag{2}
\]

\[
v = \frac{\dot{m}}{\rho_f A_0} = c_d \left[ \frac{2gL_s \sin \theta (T_f - T_r)}{(1 + A_r^2)T_r} \right]^{\frac{1}{2}} \tag{3}
\]

where,

- $c_d$ = mean coefficient of discharge of air channel inlet
- $\rho_f$ = density of air in the flow channel
- $A_0$ = cross sectional area of outlet
- $A_r$ = ratio of cross sectional area of outlet over cross sectional area of inlet
- $T_f$ = mean temperature of air in the channel
- $T_r$ = room temperature
$L_s$ = stack height
$g$ = acceleration due to gravity
$\theta$ = angle of inclination with the horizontal surface

4. Results and discussions

The experimental set up is shown in figure 4, where the absorber is heated by using a heater under constant heat flux (500W/m$^2$). A hot wire anemometer is placed below the solar chimney and at the center of the inlet opening area to measure the inlet air velocity after 1 hour heating.

Figure 5 shows that the simulation result is giving similar trend compare to experimental result. Therefore, similar simulation setting can be carried out to investigate the effect of opening areas on the performance of solar chimney. The variations in the volume flow rate with respect to opening areas are shown in figure 6 to figure 9.

![Figure 4](image)
**Figure 4.** Experimental set up to investigate solar chimney performance.

![Figure 5](image)
**Figure 5.** Experimental and simulation result for solar chimney.

![Figure 6](image)
**Figure 6.** Effect of inlet opening area on volume flow rate.

![Figure 7](image)
**Figure 7.** Effect of outlet opening area on volume flow rate (simulation).
The volumetric flow rate is lower when the inlet opening area is bigger (Figure 6). It is also found that the volumetric flow rate is higher when the inlet opening area is bigger starting from certain inlet opening area size (0.056m²). From the Figure 6, it can be concluded that bigger inlet opening area is not necessary to have better flow rate than smaller inlet opening area. Similarly, bigger outlet opening area is also not necessary to have better flow rate than smaller outlet opening area. This is shown in Figure 7 and 8 that significant flow rate is established at bigger outlet opening area for 75°, 80°, and 85°, but it is not significant when chimney angle is 90°. Therefore, it is very hard to conclude the relationship between inlet as well as outlet opening area on the volumetric flow rate of solar chimney. On the other hand, some important correlation between opening area and performance of solar chimney is found in Figure 9. From Figure 9, the ratio of inlet opening area over outlet opening area equal to two or larger is performing better than the solar chimney with the ratio lesser than two. Moreover, the volume flow rate achieve by the solar chimney does not differ much when the ratio is between 1 and 2.

5. Conclusion
Solar chimney is workable only when the solar energy is available. In order to prolong the duration either cloudy day or night time and further enhanced the natural ventilation induced, a new type solar chimney is introduced that ease its integration with the turbine ventilator. In this study, the effect of opening areas on the performance of solar chimney has been studied. One of the findings is the inlet opening area should be at least double the outlet opening area. This is due to bigger outlet opening area than inlet opening area is performing badly. Another finding is the performance of solar chimney does not differ much when the area ratio between inlet and outlet varies from 1 and 2. All those information are useful when deciding the suitable opening areas of solar chimney.

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