

# Improving the performance of solar chimney by addressing the designing factors

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**Abstract.** Solar chimney is a reliable system totally based on solar energy to enhance natural ventilation in buildings, but challenge still exists to optimize its performance with the lowest cost. In this study, three designing factors, including configuration, installation conditions, and material usages, were reviewed to provide a technical guide for engineering applications. Regarding the configuration, the performance of solar chimney can be enhanced with a high cavity, an appropriate cavity gap (usually 0.2-0.3 m), equivalent inlet and outlet area, and height/gap ratio of 10-15. Regarding installation conditions, an optimum inclination angle of 45° was usually suggested, and large openings can enhance the performance while the increasing rate keeps decreasing. The principles of material usage are to maximum the heat absorption and reduce the heat losses, considering properties such as thermal conductivity, absorptivity, emissivity, transmissivity, and reflectivity.

## 1. Introduction

Solar chimney as a reliable renewable energy system has been largely utilized to conquer the global energy crisis. Buildings represent nearly 40% of total energy use in the U.S. and about 50% of this energy is used for heating, ventilating and cooling the space. Conventional heating and cooling systems are having a great impact on security of energy supply and greenhouse gas emissions [1]. Therefore, the application of renewable energy, such as solar, wind, tides, and geothermal energy, has become a critical topic [2].

To save the traditional energy, solar chimney has been largely used to enhance the natural ventilation in buildings. It is reliable system based on solar energy, which is basically a solar air heater, its position may be vertical or horizontal and according to the position it will be a part of a wall or roof and the classification of solar chimney can be varied according to different configuration or functions [3]. Experimental results showed that a solar chimney house could reduce the average daily electrical consumption of an air-conditioner by 10-20% [4].

Although solar passive features can add 0-15% to design and construction costs, paying this initial cost in return is long life energy saving. The challenge of designing solar chimney is to optimize the performance under the lowest construction cost. One can find different variations in solar chimney design, which is affected by a number of factors such as the location, climate, orientation, size of the space to be ventilated and the internal heat gains [5].

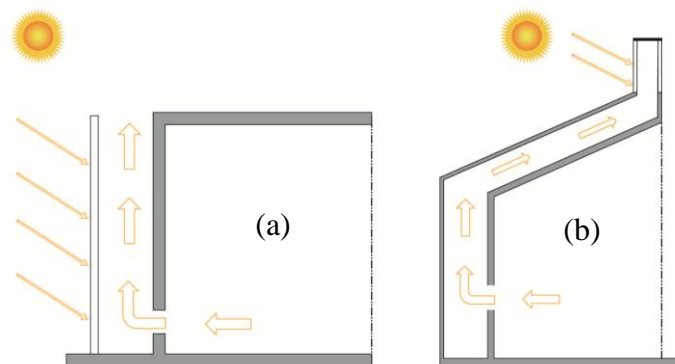
Therefore, three types of influencing factors were reviewed in this study to optimize the performance of solar chimney, including configuration, installation conditions, and material usage. The



objectives of this study is to provide a comprehensive review about the designing factor, and then to provide a technical guide for solar chimney design in sustainable buildings.

## 2. Fundamentals of solar chimney

Solar chimney is a way of enhancing the natural ventilation in buildings based on passive solar energy. The basic driving mechanism of the air flow inside a solar chimney is thermal buoyancy, which is caused by the density variation of the air due to the temperature difference between the inside and outside of the building [6]. Solar chimney is basically a solar air heater, where its position may be vertical or horizontal as a part of wall or roof, shown in Fig. 1 [7].



**Fig. 1** Two typical solar chimney used in buildings [7]: (a) wall solar chimney; and (b) roof solar chimney

Fig. 1(a) shows a schematic of wall solar chimney (Trombe wall) for winter heating. The chimney is constructed by the external glazing and the inside wall. The external glazing allows the solar radiation penetrating into the chimney for heating up. The air in the chimney cavity then moves upward under the buoyancy after they are heated. Fig. 1(b) shows a typical roof solar chimney. The performance of solar chimney is much dependent on the temperature difference between inside and outside of building. A thermal storage layer below the chimney cavity is also used to extend the heating period for cloudy days or nights. Comparing to Trombe wall, the air flow in roof solar chimney will encounter resistance because of additional bends of duct, while its advantages and disadvantage can be seen in Table 1 [7].

**Table 1.** Advantages and disadvantages of two types of solar chimney [7]

Type	Advantages	Disadvantages
Vertical solar chimney	<ul style="list-style-type: none"> <li>▪ The external glass gain sun radiation, solar collector is not needed;</li> <li>▪ The air flow in chimney could go upward directly without bends;</li> <li>▪ Easier to be control with inlet and outlet for different climatic condition; and</li> <li>▪ Stack height is not restricted by roof height.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Insulation is need to prevent direct heat transfer between chimney and interior room because of high temperature and high contact area; and</li> <li>▪ Barriers are strictly prevented because the solar gained wall is lower than roof solar collector;</li> </ul>
Roof solar chimney	<ul style="list-style-type: none"> <li>• Very large collector areas easily achieved;</li> <li>• May be more aesthetically pleasing than a tower;</li> <li>• No additional towers needed;</li> <li>• Likely to be cheaper than a tower design; and</li> <li>• Easier to retrofit.</li> </ul>	<ul style="list-style-type: none"> <li>• Stack height is restricted by roof height;</li> <li>• Heat transfer between heated air and glass is higher than for a vertical surface;</li> <li>• Additional bends create greater pressure-losses; and</li> <li>• Incorporation of thermal mass may be more difficult.</li> </ul>

## 3. Influencing factors of solar chimney

### 3.1. Configuration

It is quite sure that a higher cavity height can result in a better performance for wall solar chimney. Several reasons may be explained for this. The first is due to the pressure difference distribution enhanced by the high cavity, resulting in the rising of ventilation rate [8]. The increased heat gain is another reason where an increase in wall height by a quarter is equivalent to an increase in heat gains by three quarters [9]. The situation for roof solar chimney may be a little different. An experiment showed that there exists an appropriate cavity length, beyond which the obtained heat and natural ventilation rate cannot be increased drastically [10].

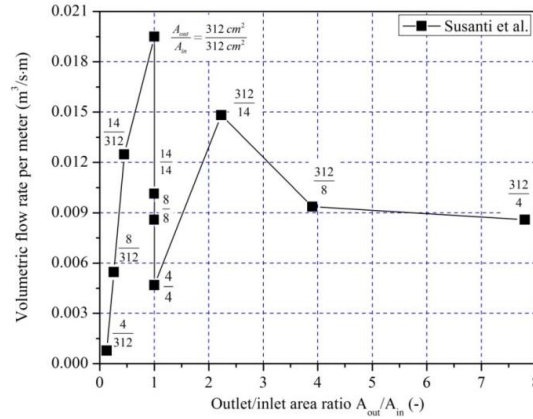
Cavity gap, also called chimney width or channel depth in the literatures, is the thickness of roof duct and the distance between the inside wall and external glazing for roof and wall solar chimney, respectively. The performance of both wall and roof solar chimney are highly influenced by the cavity gap. Studies have been carried out on finding out the optimum cavity gap. Many studied [11, 9, 12, 13] suggested a cavity gap of 0.2-0.3 m to achieve the maximum performance of solar chimney. This statement has been made based on a viewpoint of solar chimney design that the maximum effect with lower material costs is achieved under this cavity gap [13], or the stack effect that the stack effect is maximum when the cavity gap is within this range [14, 15].

Inlet and outlet areas are determining factors for the air entrance and escape. Within a certain range of cavity gap, both inlet and outlet areas show positive influences on the performance of solar chimney. An analytical analysis by Bassiouny and Koura [16] concluded that increasing the inlet size three times can improve the performance by almost 11%. Another experimental study also showed that the ventilation flow rate increased with an increase in ventilation inlet area [17]. Based on both experimental [18] and numerical [19] studies, it is noted that optimized ventilation flow rate can be obtained when the outlet area takes the same area as the inlet area. For unequal openings, the outlet area shows a higher importance than inlet area to enhance the air flow in the cavity, shown in **Fig. 2** [20, 18].

Chimney aspect ratio usually refers to the ratio between the cavity height and cavity gap thickness. Previous studies have been undertaken to find the optimum aspect ratio. A optimum ratio of 10 was obtained from both numerical modelling [19, 21] and experiments [22]. For roof solar chimney, Du et al. [23] obtained that the optimal length to width ratio of a chimney is 12 based on numerical modelling. For the solar collector on the top roof, the ratio of solar chimney's length to hydraulic diameter should be greater than 15 to ensure developed flow [24].

### 3.2. Installation conditions

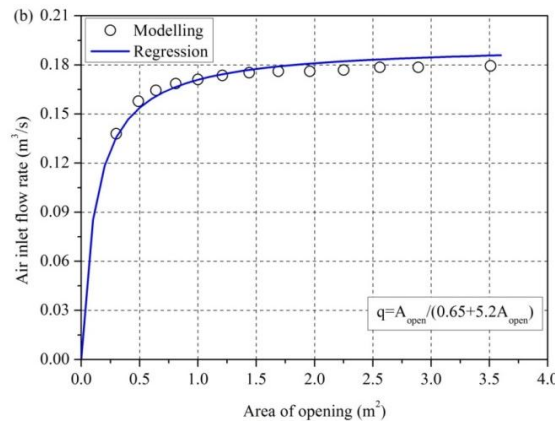
Inclination angle for solar chimney generally refer to the angle between cavity and the horizontal. It is usually applicable to roof solar chimney. As the roof solar chimney should be assembled with roof, the inclination angle is much dependent on the inclination angle of the roof, shown in Fig. 1(b). The optimum inclination angle is one of the key influencing factors on the performance of solar chimney. Most of the previous studies obtained an optimum inclination angle of 45° [25, 26, 2, 27, 10]. Its airflow rate is about 45% higher than that for a vertical chimney at otherwise identical conditions [25, 26], which was explained by lowest pressure loss. Zhai et al. [10] explained this as a balance between the stack pressure and convective heat transfer coefficient.



**Fig. 2** The influence of outlet/inlet area ratio on volumetric flow rate per meter [20, 18]

Opening usually refers to the window, door, skylight, and other styles that can bring in fresh air in the buildings. The function of the opening of the room is to promote the circle of airflow, which benefits the natural ventilation and heat exchange in buildings. Priyadarsini et al. [28] found from experiments that even though the enhancement in the velocity is much higher when the doors are closed, they are more or less localized as the velocity increase is more evenly distributed when the doors are kept open.

In our previous study [29], a room coefficient ( $C_R$ ) is proposed to describe the influence of both the room configurations on the performance of wall solar chimney. It can be seen from our numerical results that the inlet flow rate increases dramatically with the area of opening initially but the rate of increase then slows down at a later stage, shown in **Fig. 3**.



**Fig. 3** The influence of opening on the air inlet flow [29]

The empirical model developed in our previous study can be expressed by [29]:

$$Q_{in}^* = C_R \cdot [h \cdot H_{sc} \cdot A_{hot} \cdot (T_{sc} - T_0)]^{1/3} \quad (1)$$

where  $C_R$  is the room configuration coefficient related to room openings, chimney inlet and outlet,

$$C_R = \frac{0.1 + 0.0016A_r - 0.003A_r^{-1}}{9.9 + 1.5A_{open}^{-1}}, \text{ where } A_r = \frac{A_{in}}{A_{out}} \quad (2)$$

### 3.3. Material usages

Glazing is largely used in both wall and roof solar chimney, shown in Fig. 1(a) and (b). For the glazing, several properties may be important to the performance of solar chimney, such as transmissivity, reflectivity and absorptivity. An experimental study by Lee et al. [2] showed that a high transmissivity

of glass can increase the outlet temperature and improve the performance of collectors, which showed a relatively higher importance than the reflectivity and absorptivity.

Double glazing shows its advantage in enhancing the performance of solar chimney. Hatami and Bahadorinejad [30] assessed six cases of air flow including: two cases for air heaters equipped with one glass cover and four cases for air heater with two glass covers. Maximum efficiency was obtained when air heaters had two glass covers and air could flow through all channels. Although double glazing shows advantage, it seems to be a good choice for winter heating but not for summer cooling [9, 5].

Materials have been also utilized in solar chimney for several special functions, such as thermal insulation, thermal storage and thermal absorption. It is known that a thermal storage layer with phase change materials under the cavity is to absorb as much heat as possible from the hot air in the cavity. It can release the heat at a later stage when the phase changes back. The bottom layer of insulation is to minimize the heat loss for the storage layer.

For solar collector, the solar absorptivity and emissivity play important role for the performance of roof solar chimney. Lee and Strand [31] reported the effect of absorptivity on ventilation enhancement and showed that improvement in air flow rate can be up to 57% by increasing the solar absorptance of the absorber wall of a solar chimney from 0.25 to 1.0. This was also confirmed by Liu et al. [32]. The numerical results [6] showed that the mass flow rate is an increasing function of surface emissivity and input heat flux and the mass flow rate is up to 59% higher with a surface emissivity of 0.9 than that with a zero surface emissivity.

Thermal insulation has been investigated regarding the performance of solar chimney. An experimental study showed that decreasing the heat transfer resistance in the airflow channel had the most significant effect on thermal efficiency enhancement, comparing to other four parameters, including height of a stagnant air layer, optical properties of a transparent cover, emissivity of an absorber plate, and conductive thermal resistance of a back plate on the thermal performance of a solar air collector [33].

The optimum thickness of wall was also investigated. A numerical study taken by Afonso and Oliveira [34] suggested that a thickness of 5 cm insulation wall is sufficient and no significant improvements can be achieved with thickness above 10 cm. It was mentioned that the optimum storage thickness for solar chimney depends on building use pattern. A small thickness was suggested for daytime ventilation, whereas, greater thickness was suggested for night time ventilation. An insulation thickness of 5 cm was considered optimum.

#### 4. Conclusions

Solar chimney is a reliable system to enhance the natural ventilation in buildings totally based on solar energy, which plays an important role in release the global energy crisis. Although a large number of studies have been undertaken, the optimization design is still a challenge regarding solar chimney. Therefore, three important designing factors, including configuration, installation conditions, and material usages, were reviewed to provide a technical guide for engineering applications. In the aspect of the configuration, improved performance of solar chimney can be achieved for a high cavity, an appropriate cavity gap (usually 0.2-0.3 m), equivalent inlet and outlet area, a range of height/gap ratio (usually 10 for wall solar chimney and 12-15 for roof solar chimney). Regarding installation conditions, an optimum inclination angle of 45° was usually suggested, and opening of the room can enhance the performance but the increasing rate will slow down when it approaches to value. Materials used for solar chimney play an important role for the performance, such as thermal conductivity, absorptivity, emissivity, transmissivity, and reflectivity. Double glazing shows advantage, but it is a good choice for winter heating but not for summer cooling.

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