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Determining the influencing factors on the performance of solar chimney in buildings

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Abstract: Solar chimney as a reliable renewable energy system has attracted increasing attention from engineers to conquer the current energy crisis. The main challenge of designing a solar chimney is to optimize its performance with the lowest cost. Based on literature review, thirteen key influencing factors were obtained and classified into four groups, including configuration, installation conditions, material usage, and environment. Statistics of experimental studies showed that the overall tested range is still limited which suggests more future experiments. To enhance the performance, a solar chimney is suggested with possible high cavity and solar radiation, a cavity gap of 0.2-0.3 m, equal inlet and outlet, a height/gap ratio of around 10, an inclination angle of 45-60° (for roof solar chimney considering latitude), an appropriate opening of room, double/triple glazing, a 5 cm thick insulation wall, and a solar absorber with larger absorptivity and emissivity. These optimum values may not be applicable to all configurations as they are interdependent. Although external wind shows significant influence on solar chimney, solar chimney design can be undertaken without considering the effects from wind. This review will provide a useful technical guide for researchers and professionals regarding the optimum designs of solar chimney in buildings.

Keywords: solar chimney; configuration; installation condition; material usage; environment; optimum design.

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1. Introduction

Solar chimney as a reliable renewable energy system has been largely utilized in buildings under the fact of serious environment problem and energy crises with the continued exploitation and overuse of fossil energy [1-4]. This is because buildings can consume about 42% annual energy usage of the whole world, mainly for heating, cooling, providing electricity and air conditioning [5]. Conventional heating and cooling systems have a great impact on the security of energy supply and greenhouse gas emissions [6].

Natural ventilation is one of the significant sustainable building design strategies and has been known to mankind for several hundred years [7-9]. One of the sustainable strategies for a building to reduce energy consumption is to enhance the natural ventilation in the surrounding spaces based on solar chimney [10-13]. As a simple and practical strategy, it has been receiving considerable attention to decrease heat gain and induct natural ventilation (cooling or heating) in both residential and commercial buildings because of its potential advantages regarding operation cost, energy requirement and emission of carbon dioxide [14, 15].

Solar chimney is based on natural convective air movement forced by the pressure gradient caused by air density variation between indoor and inside the chimney cavity, acting as a natural ventilation system, passive heating method, or thermal insulation device [16]. It is fundamentally a solar air heater with vertical or horizontal configuration as a part of wall or roof, while the classification of solar chimney can be varied according to different configurations or functions [17]. It generates air movement under buoyancy forces that hot air rises and exits from the top of chimney cavity, drawing cooler air into building with continuous cycle [18].

A solar chimney house could reduce average daily electrical consumption of an air-conditioner, for example a study stated a reduction rate of about 10-20% in Thailand [19]. The air temperature in a room can also be reduced about 8.5 °C averagely after utilizing solar chimney [20]. Although it could add 0-15% cost to the design and construction of the building, paying this cost in return is a life-long energy saving. Due to the natural ventilation induced by solar chimney, the daily fan shaft requirement in a house located in Tokyo can be reduced by 90% in January and February with a 1 m wide solar chimney, while the reduction throughout the year was obtained of about 50% [21].

Now the main challenge of designing a solar chimney is to optimize its performance with the lowest cost. However, one can find a large amount of variations in solar chimney design [22]. Therefore, in this study, thirteen key influencing factors were obtained based on literature review which can be classified into four groups, including configuration (height, cavity gap, inlet and outlet areas, and height/gap ratio), installation conditions (inclination angle, opening of the room, and solar collector), material usages (type of glazing, materials of solar absorber, and thermal insulation), and environment (solar radiation, external wind and other climatic conditions).

Besides the solar chimney mentioned above, there is another type of solar chimney, which follows the same principles and is called solar chimney power plant [23-25], standing independently as a system for big-scale usage. This literature review will focus on the first type, namely solar chimney attached to a building. The objective of this literature review is to identify key influencing factors and address their influences on the solar chimney performance, and eventually to provide a technical guide for its design in buildings.

2. Fundamentals of solar chimney

2.1 Types of solar chimney

Solar chimney is an approach to enhance the natural ventilation in buildings based on passive solar energy. The basic driving mechanism of the air flow inside chimney cavity is thermal buoyancy, which is caused by air density variation under temperature gradient between the inside room and chimney cavity [26]. Fig. 1 shows the typical solar chimneys used in buildings. It should be noticed that solar chimneys coupled with other systems were not included. It can be seen that three categories can be found, implemented in wall, roof and window. The tree categories are: (1) Trombe wall; (2) roof solar chimney; and (3) combined solar chimney.

Fig. 1(a) shows a schematic of Trombe wall (Category 1) for winter heating. It is constructed by external glazing and internal storage wall. The external glazing allows solar radiation penetrating into chimney cavity for heating purpose. Air in the cavity then moves upward under thermal buoyancy. The air enters the room under buoyancy drive through top opening. Opening at bottom left keeps open to benefit air exchange with outside environment, while the one at bottom right is for air exchange with inside room. Trombe wall can also be applied to summer cooling after changing the location of openings, and its structure is similar to that of Fig. 1(c). Under this circumstance, hot air in the room can exhaust to outside environment through the chimney. An innovative design of Trombe wall is to use phase change materials (PCM) to keep the latent heat of a storage wall, which require less space and are lighter in weight when comparing to those mass walls [27].

Based on Trombe wall, a composite Trombe-Michel wall was also developed, shown in Fig. 1(b). It was designed to overcome heat losses from the inside room. Due to its structure, it can only be applied for winter cooling. One of its disadvantages is that it cools the building when it actually needs to heat it up during night or winter when the storage wall becomes colder than the indoor air [28]. To overcome the disadvantage, relevant materials such as PCM could be used to keep the heat for later usage during non-sunny days, winters or at nights [29]. Different from the Trombe wall, movable air in the chimney cavity is not heated by direct solar radiation, but the convection processes between the internal air and the massive wall.

A glazed solar chimney wall can be utilized under tropical climatic conditions, as shown in Fig. 1(c). It consists of double glass panels with an air layer and openings located at the bottom (room side glass panel) and at the top (ambient side glass panel). The basic mechanism of the glazed solar chimney wall is the same with the Trombe wall. Its performance in tropical area is confirmed by experiment that it can reduce heat gain through glass walls into the house by developing air circulation [30]. However, as the performance of a solar chimney is much dependent on its height and width, its applications under other climatic conditions may be hampered because of weak performance due to limited size.

Fig. 1(d) shows a typical roof solar chimney (Category 2). As the performance of a solar chimney is much dependent on the temperature difference, a solar air heater (collector) at the roof is used to maximize the temperature difference. A glazing is used externally to heat the air in the cavity by absorbing solar radiation. A thermal storage layer below the chimney cavity is to extend heating period for late usage such as during cloudy day or night. An insulation layer at the bottom is to minimize the heat loss from storage layer. It should be noticed that this kind of roof solar chimney can be inclined (Fig. 1(d)) or vertical (Fig. 1(e)), depending on implementations. Comparing to the Trombe wall, air flow in roof solar chimney encounter further resistance because of additional bends of duct, while its advantages and disadvantage can refer to Reference [3].

Fig. 1(e) shows a vertical roof solar chimney. Its difference from conventional roof solar chimney is an extra vertical chimney utilized as an inlet. Both inlet and outlet are realized through two chimneys coupled with roof; where one collects solar radiation and the other is a conventional chimney for inlet. Alternatively, the inlet (or opening) of room can be in a form of window, door or the like on the other side. This roof solar chimney may be applicable to some special situations [31]. Its challenge is to circulate the whole room as short circulation (or partial ventilation at the top of the room) may happen when both the inlet and outlet are located at the same height.

Solar chimney shown in Fig. 1(f) is a combined solar chimney (Category 3) including both vertical and roof chimneys. Vertical solar collector is located above roof, and ducts are collected along the wall and roof. Air inside the room can exhaust to outside directly through the top vertical solar collector, or through the ducts and then to the solar collector. Opening to supply fresh air from outside is on one side of the wall, shown in the middle of the figure. The performance is dependent on the temperature difference which the vertical solar collector can produce, relying on its size and materials usage. Similar to other roof solar chimney, reducing the resistance caused by the bended duct is still one of the main challenges [32].

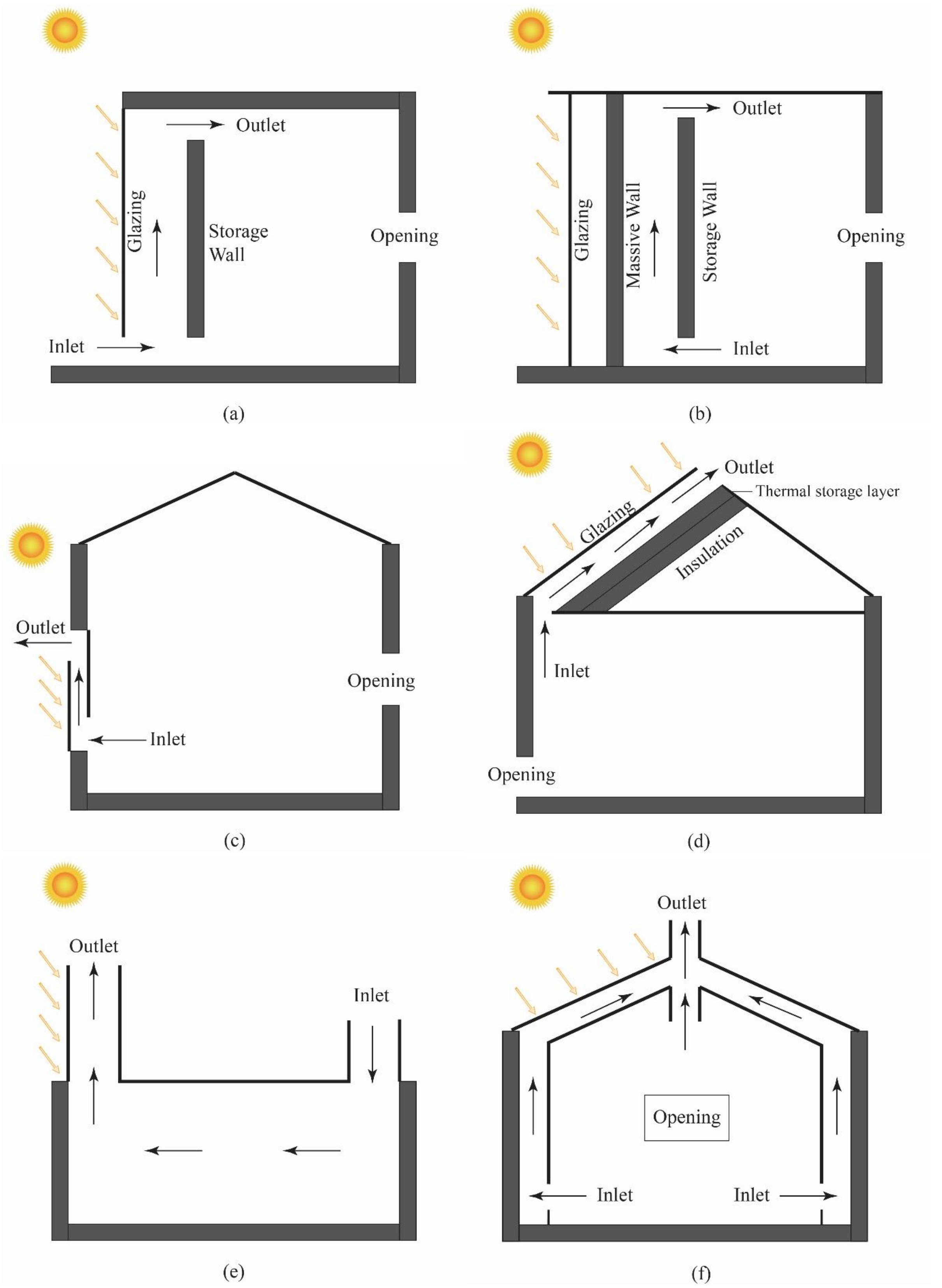


Fig. 1 Typical solar chimneys used in building. Category 1 is the Trombe wall which includes (a), (b), and (c); Category 2 is the roof solar chimney shown in (d) and (e); and Category 3 is the combined solar chimney represented by (f).

2.2 Testing ranges of influencing factors

Table 1 shows a summary of tested ranges for influencing factors in previous experimental studies, including both roof and wall solar chimney. It should be noticed that only experiments with parametric study were included in this table, which may not be the full list from the literature. In this table, inclination angle is the angle between roof solar chimney and the horizontal, and wall solar chimney is considered an inclination angle of 90°.

Based on literature review, eight influencing factors were found having been analysed in previous experimental studies, including inclination angle, cavity gap, height, height/gap ratio, inlet area, outlet area, inlet/outlet ratio, and solar radiation. Seven out of eight factors have focused on the influences of configuration and installation conditions, leaving one regarding the environment (solar radiation). Very few tests have been taken regarding material usages and environment. Although solar radiation of 20-1,057 W/m^2 is enough to address most of the solar radiation conditions, a test range of chimney height of 0.521-2.07 m is only applicable to single storey buildings. In addition, the inlet/out ratio of 0.093-23.0 is not enough to cover all the necessary cases. Based on this table, it can be known that more experiments are critically needed in the future, especially on material usages, environmental factors, chimney height, and inlet/outlet ratio.

Previous experimental tests can be classified into two types: laboratory and outdoor tests. For the laboratory test, experiments were taken in a stable environment. For example, Bouchair [33] conducted the tests in a laboratory considered large enough (20 m long × 10 m wide × 5 m high) to simulate a steady state environment. Somsila et al. [34] conducted the experiment in indoor environment and used the equipment to produce the light intensity instead of exposing directly to the sunlight. In some experiments [35-38], to simulate solar radiation, the bottom of the cavity was heated up using an electric heating plate. Some experiments may need a long time period to achieve steady state. For example, Susanti et al. [35] ran the tests for over 20 hours to obtain the data after a steady condition was achieved in their experiments.

For those outdoor tests, data were obtained by a long time period tests in outdoor environment under solar radiation. For example, Saifi et al. [39] carried out outdoor tests between 9am until 4pm with steps of 30 minutes. Imran et al. [40] installed roof solar chimney to a 2 m (width) × 3 m (length) × 2 m (height) room, collecting data during daytime from 7am to 2pm in several days. A solar power meter was positioned parallel to the chimney cavity, quantifying the received solar radiation [40]. Outside environment could be significant to experimental outputs, and many measures were used to minimize the influences. For example, to reduce the effects from the external wind, Bansal et al. [41] placed a wall with a size of double height and triple width comparing to the solar chimney model on its suction side.

Table 1 A summary of tested ranges for influencing factors in previous experimental studies

Influencing factor	Unit	Overall range	Studied range[a]
Inclination angle[b]	°	10-90	• 10-90 [36]; 15-60 [40]; 30-45 [39]; 30-90 [42,

			43].
Cavity gap	m	0.02-1.2	• 0.02-0.11 [38]; 0.02-0.15 [44, 45]; 0.05-0.15 [40]; 0.1-0.14 [46]; 0.1-0.145 [47, 48]; 0.1-0.3 [39, 43, 49, 50]; 0.1-0.5 [36]; 0.1-0.6 [42]; 0.1-1.0 [33]; 0.13-0.332 [41]; 0.4-1.2 [51].
Height	m	0.521-2.07	• 0.521-2.07 [44]; 0.7-0.9 [49]; 1.0-2.0 [34][47][48].
Height/gap ratio	-	1.7-103.5	1.7-5.0 [51]; 2.0-20.0 [33]; 2.3-9.0 [49]; 2.5-15.0 [42]; 3.0-5.0 [36]; 3.0-7.7 [41]; 3.3-25.0 [45]; 3.5-103.5 [44]; 6.6-19.8 [50]; 6.7-20.0 [39, 43]; 6.9-20.0 [47, 48]; 9.3-51.3 [38]; 10.0-20.0 [34]; 13.3-40.0 [40]; 14.3-20.0 [46].
Inlet area	m^2	0.019-1.2	• 0.019-0.102 [38]; 0.02-0.15 [44, 45]; 0.05-0.25 [36]; 0.062-0.372 [42]; 0.1-0.3 [39, 40, 43, 49]; 0.13-0.235 [41]; 0.14-0.56 [33]; 0.4-1.2 [51].
Outlet area	m^2	0.016-1.5	• 0.016-0.377 [52]; 0.02-0.15 [44, 45]; 0.045-0.135 [50]; 0.05-0.25 [36]; 0.062-0.372 [42]; 0.1-0.3 [39, 40, 43, 49]; 0.13-0.332 [41]; 0.15-1.5 [33]; 0.4-1.2 [51].
Inlet/outlet ratio	-	0.093-23.0	• 0.093-3.733 [33]; 0.333-1.0 [50]; 0.33-3.0 [49]; 0.39-1.81 [41]; 1.0-23.0 [52].
Solar radiation	W/m^2	20-1057	• 20-300 [52]; 50-150 [35]; 73-374 [37]; 100-500 [43]; 120-650 [36]; 150-750 [40]; 188-1057 [44]; 200-400 [42][51]; 200-650 [50]; 200-925 [45]; 200-1000 [38]; 205-762 [41]; 300-700 [49]; 400-800 [34]; 500-700 [53]; 500-750 [54].

Note: [a] This table only includes the experiments with parametric studies, ignoring fixed configuration; and [b] Inclination angle is the angle between roof solar chimney and the horizontal.

2.3 Mathematical models

Mathematical models have been utilized to predict the performance. These models derived from mathematical deduction, or correlation based on experimental or numerical results. Table 2 shows a summary of typical mathematical models from the literature. For a better comparison, all these models are converted to predict volumetric flow rate in the chimney cavity if they were not in this form originally. A schematic revised from original source was provided for each model to show the applicability, as listed in the fourth column of Table 2.

Based on literature review, four types of mathematical models were found in the literature, shown in Table 2, determined by their modelling inputs:

- The first type of models (Type I in Table 2) shows proportional relationship between airflow rate and individual parameter;
- The second type of models (Type II) predicts volumetric flow rate based on air temperature in the cavity. Although they may have various forms, their predictions are much dependent on temperature differences, inlet and outlet areas, cavity height, and

inclination angle (for roof solar chimney). Their applications may be limited sometimes because of those difficult-to-get inputs, such as wall friction coefficient and pressure loss coefficient;

- The third type (Type III) is density based predictions where the air densities inside and outside of chimney cavity were used for the modelling inputs. This type shows a similar form with the second type, replacing air temperature with air density; and
- The last type (Type IV) is based on solar radiation. Similar to the previous two types, a lot of coefficients were used for modelling inputs.

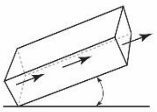
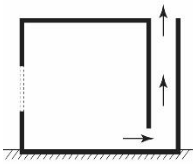
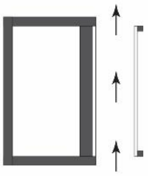
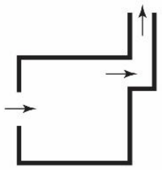
Those Type II models shown in Table 2 were developed based on only cavity configuration, without considering room configuration. To solve the problem, Shi and Zhang [55] developed a model considering both room and chimney configurations with easy-to-obtain inputs,

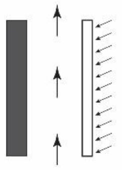
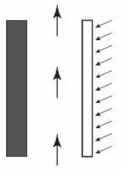
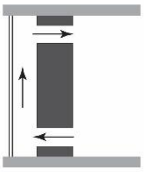
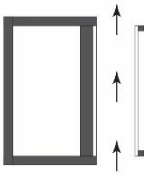
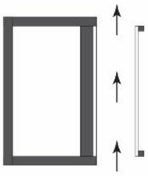
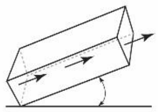
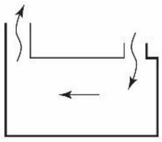
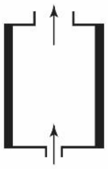
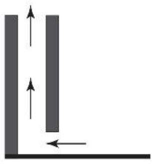
$$V = C_{room}\left[hHA_{hot}\left(T_{wall} - T_0\right)\right]^{1/3} \qquad (1)$$

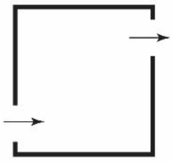
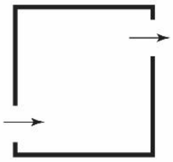
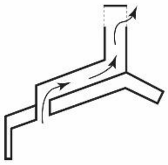
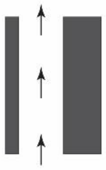
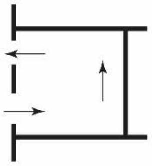
where h is the heat transfer coefficient of cavity wall, W/m^2·°C; A_{hot} is the area of hot cavity wall; T_{wall} is the temperature of cavity wall, °C; and C_{room} is the room configuration coefficient, which can be obtained by:

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

Table 2 A summary of typical mathematical models for solar chimney

Reference	Year	Type	Schematic	Equation
Shi et al. [56]	2016	IV		$V = \frac{w\ \sin\theta'^{\ 1/3} q^{1/2} d^{0.7} H^{2/3}}{Slope}$
Shi and Zhang [55]	2016	II		$V = C_{room}\left[hHA_{hot}\left(T_{wall} - T_0\right)\right]^{1/3}$
Ryan and Burek [57]	2010	I		$V \propto q^{0.459};\ V \propto d^{0.756};\ V \propto H^{0.600}$
Dimoudi [58]	2009	II		$V = 23.37A_{in}A_{out}\sqrt{\frac{gH\left(T_c - T_0\right)}{\left(k_{in}A_{out}^{\ 2} + k_{out}A_{in}^{\ 2}\right)T_0T_c}}$

Sankonidou et al. [59]	2008	III		$V = sin\theta A_{out}\sqrt{\frac{2gH\ \ \rho_0-\rho_c}{\left(f\frac{H}{d}+k_{in}+k_{out}\right)\rho_c}}$
Sankonidou et al. [59]	2008	II		$V = C_d sin\theta\frac{\rho_c}{\rho_0}A_o\sqrt{\frac{gH\left(T_c-T_0\right)}{T_0}}$
Shen et al. [28]	2007	II		$V = C_d A\sqrt{\frac{gH\ \ T_{out}-T_{in}}{T_{out}+T_{in}}}$
Burek and Habeb [38]	2007	I		$V \propto Q^{0.572};\ V \propto d^{0.712}$
Ryan et al. [45]	2005	I		$V \propto q^{0.452};\ V \propto d^{0.652};\ V \propto H^{0.539}$
Halldorsson et al. [60]	2002	IV		$V = A\left(\frac{gqwsin\theta H^2}{A\rho C_p T_0\left[f\frac{H}{d}+k_{in}\left(\frac{A}{A_{in}}\right)^2+k_{out}\left(\frac{A}{A_{out}}\right)^2\right]}\right)^{1/3}$
Afonso and Oliveira [31]	2000	II		$V = \frac{A_{out}\sqrt{2\alpha g\left(T_c-T_0\right)H}}{\sqrt{k_{in}\left(\frac{A_{out}}{A_{in}}\right)^2+k_{out}+f\left(\frac{H}{d}\right)}}$
Sandberg and Moshfegh [61]	1998	IV		$V = A\left[\frac{gqH^2 sin\theta}{\rho_0 C_p T_0 d\left(2f\frac{H}{d}+k_{in}+1\right)}\right]^{1/3}$
Gan [62]	1998	I		$V = 143.4w^{0.6582}$ $V = 4.5725q^{0.4015}$ $V = 17.84\sqrt{H-2.28}+24.86$

Andersen [63]	1995	II		$V = C_d A_{in}\sqrt{\frac{2gH(T_c - T_0)}{T_c}}$
Andersen [63]	1995	IV		$V = 0.037(QH)^{1/3}(C_d A_{in})^{2/3}$
Bansal et al. [64]	1993	II		$V = C_d A_{out}\sqrt{\frac{2(T_c - T_0)gHsin\theta}{T_0(1+A_r^2)}}$
Awbi and Gan [65]	1992	II		$V = C_d A\sqrt{\frac{4gH(T_c - T_0)}{T_c}}$
BS 5925 [66, 67]	1991	II		$V = C_d\left[\frac{A_{in}A_{out}}{\sqrt{(A_{in}^2 + A_{out}^2)}}\right]\sqrt{\frac{2gH(T_c - T_0)}{T_0}}$

Note: ***A*** is the area, m^2; ***C*** is the coefficient; ***C$_p$*** is the specific heat capacity, J/kg·°C; ***d*** is air gap thickness, m; ***f*** is the wall friction coefficient; ***g*** is the gravitational acceleration, m/s^2; ***H*** is the cavity height, m; ***h*** is the heat transfer coefficient, W/m·°C; ***k*** is the pressure loss coefficient; ***q*** is the heat input intensity, W/m^2; ***Q*** is the heat input, W; ***Slope*** is the regression slope determined by four influencing factors, and the details can be seen in Reference [56]; ***T*** is the temperature, °C; ***V*** is the volumetric flow rate, m^3/s; ***w*** is the cavity width, m; ***α*** is the thermal expansion coefficient, 1/°C; ***θ*** is the inclination angle from the horizontal, °; ***θ'*** is the calculated inclination angle, and the calculation can be seen in Reference [56], °; and ***ρ*** is the density, kg/m^3. Subscripts: ***0*** – ambient conditions; ***c*** – cavity; ***d*** – discharge; ***hot*** – hot cavity wall; ***in*** – inlet; ***out*** – outlet; ***r*** – ratio between outlet and inlet; ***room*** – room configuration; and ***wall*** – cavity wall.

Please note the *Q* is the total heat input in *W* which is different from the *q* (heat input per unit area in W/m^2), same as follows.

2.4 Methodology of literature review

The literature review in this study is serving the purpose of identifying the main influencing factors and their effects on the performance of solar chimney when it is attached to a building. To ensure the comprehensiveness, several principles were followed during the literature review:

- Using a comprehensive database. Google scholar was used to search for journal papers, conference proceedings, technical reports, and so on, without limiting the documentation type and publication year;

- Searching based on general keywords. Some simple keywords were used to avoid the exclusion of key documentation, such as "solar chimney", "building", and "performance";
- Trying to avoid numerical results unless with limited information. We have tried our best to analyse those influencing factors based on experimental data, unless there are limited information available regarding the specific factor;
- Focusing on solo solar chimney in building. To appropriately address the individual influencing factor, solar chimney combined with other systems, such as photovoltaic panel and air heat exchanger, were excluded from the analysis. Solar chimney power plant was also excluded from this study;
- Rechecking factors based on mathematical models. To ensure the comprehensiveness of the influencing factors, the development processes of mathematical models (as shown in Table 2), such as assumptions, mathematical formulation and inputs, were carefully checked to ensure the completeness of influencing factors.

After exhausting the literature and mathematical models, four groups influencing factors were obtained, including configuration, installation conditions, material usages, and environment. Each group includes three to four factors which makes it total thirteen. Those influencing factors and their effects on solar chimney performance are summarized and analysed in the following sections.

3. Influences of configuration

3.1 Height

The height for wall solar chimney refers to the vertical height of chimney cavity. It is quite sure that a higher height can result in a better performance. Several reasons may be explained for this. The first is due to the pressure difference enhanced by high chimney cavity, resulting in the rising of ventilation rate [68]. The increased heat gain is another reason. Gan [62] observed an increase of heat gains by three quarters after increasing the wall height by a quarter.

Many studies have confirmed the same result. A double ventilation flow was observed in experiments when chimney height is doubled [69]. AboulNage and Abdrabboh [70] analysed theoretically a chimney with heights within 1.95-3.45 m, and obtained the maximum air flow rate of 2.3 m^3/s happens at a chimney height of 3.45 m. A numerical study by Lee and Strand [71] stated that air flow rate increases by about 73% when the wall height rises from 3.5 m to 9.5 m with a 0.3 m cavity gap. Al-Kayiem et al. [72] obtained numerically that the maximum air velocity rises from 3.47 m/s to 4.5 m/s when height rises from 5 m to 15 m. Therefore, Du et al. [73] suggested to select the longest vertical length as possible within the restriction of building codes to achieve the best performance.

Based on those previous models listed in Table 2, it can be known that the volumetric flow rate is linear to $H^{1/2}$, $H^{0.539}$, $H^{0.6}$, or $H^{2/3}$. Shi et al. [56] indicated based on experimental data from various test rigs that the volumetric flow rate correlates the best with $H^{2/3}$,

$$V \propto H^{2/3} \tag{3}$$

Thermal efficiency of solar chimney is also improved under an increased height. Thermal efficiency of a solar chimney is the ratio between heat gained by the air in the chimney cavity and the input heat from the solar radiation [38], and its calculation of a specific solar chimney can refer to Reference [74]. From both experiment and numerical modelling, Somsila et al. [34] found that the thermal efficiency increases from 33% to 38% when the cavity height increases from 1 m to 2 m under a solar radiation of 800 W/m^2, while the increase rate seems to be similar under a lower radiation of 400 W/m^2 that the efficiency increases from 28% to 33%.

Applications of wall solar chimney in multiple storeys buildings have also been analyzed. Results are the same with single storey building that a higher height can enhance the performance. As shown in Fig. 2, Punyasompun et al. [75] investigated two configurations of solar chimney in multiple storeys building by experiments: one is the solar chimney with an inlet and outlet installed at each floor (Fig. 2(a)); and the other one is a tall solar chimney with an inlet at each floor and one jointed outlet at the top floor (Fig. 2(b)). It was known that the second configuration with single outlet at the top shows a relatively better performance than the other. This is consistent with the above analysis that a single storey building with a higher cavity can induce more air flow, and extra outlets at lower height may bring in more pressure losses due to the short circuit.

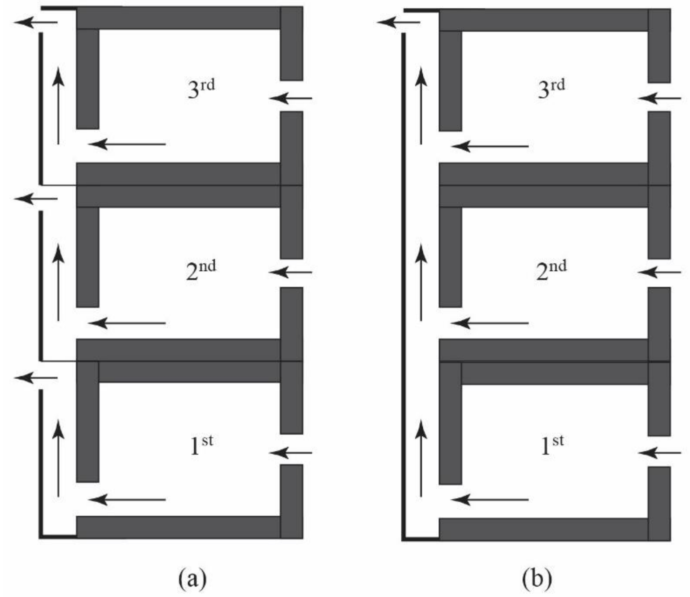


Fig. 2 Two chimney configurations for multi-storey building: (a) separated solar chimney; and (b) combined solar chimney. Figure was revised from Reference [75].

The height of roof solar chimney can be the length of inclined cavity or solar collector above roof. Few studies have been found on its cavity height. The trend for roof solar chimney may be different from that of wall solar chimney. An experiment [36] showed that an appropriate cavity length is existing, missing which the both heat absorption and follow-up ventilation performance cannot be increased drastically. This is also reflected by the measured temperature that the rising rate gradually slows down when the length reaches 1 m. Air flow rate in the cavity then decreases because of the dropped efficiency of heat collection after the length approaches to a value.

3.2 Cavity gap

Cavity gap, also called chimney width or channel depth in the literature, is the thickness of roof duct or the distance between the inside wall and external glazing for roof and wall solar chimney, respectively. The performance of both solar chimneys is highly influenced by the cavity gap. Experiments by Ong and Chow [50] showed that a 0.3 m cavity gap is able to provide 56% more ventilation than that of 0.1 m. Halldorsson et al. [60] indicated that by changing the cavity gap (0.1-0.6 m) while maintaining all the other conditions, the airflow rate increases continuously with increased gap. When the cavity gap increases from 0.07 to 0.35 m, Balocco [76] obtained based on her in-house model that the over-heating reduction rises from 7% to 27.5% during summer.

Bassiouny and Koura [77] identified cavity gap as a significant parameter on solar chimney performance in terms of air change per hour. An experiment conducted by Burek and Habeb [38] quantitatively addressed the influence of cavity gap on the airflow rate, based on an experimental setup with a vertical open-ended channel and closed side,

$$V \propto d^{0.712} \tag{4}$$

Shi et al. [56] also obtained a similar result for roof solar chimney based on experimental data from various test rigs. The relationship can be expressed by:

$$V \propto d^{0.7} \tag{5}$$

Airflow rate in the cavity not always increases with a bigger cavity gap. For example, a numerical study [71] indicated that as cavity gap width increases from 0.15 to 0.75 m, the air flow rate decreases by 1.9-4.7% in Minneapolis, Spokane and Phoenix of USA, respectively. This is because of the occurrence of reverse flow. As the heating of the air in the cavity is dependent on convection processes, the air adjacent to the hot wall get more chance to be heated. The convective heat transfer from the hot wall to the movable air is relatively limited in the middle of cavity under a bigger cavity gap. The temperature difference and frictions between the two air layers are the two main reasons for reverse flow.

Total mass flow rate through a vertical chimney cavity is greatly influenced by reverse flow occurring near its exit, and penetration depth of the reverse flow is dependent on the Rayleigh number [78]. Zhai et al. [36, 79] observed reverse flow in a experimental setup with a 0.2 m cavity gap. Imran et al. [40] did not observe reverse air flow circulation from numerical modelling with a 0.15 m cavity gap. Ong and Chow [50] stated that no reverse air flow circulation was observed even at a large gap of 0.3 m based on experiment. Chen et al. [42] confirmed the reverse flow occurring from chimney outlet for a 0.4 m cavity gap through flow visualization experiment.

Studies have been carried out on finding out the optimum cavity gap. This is highly necessary in the perspective of both the performance and construction cost. Many studied [21, 49, 62, 80, 81] suggested a cavity gap of 0.2-0.3 m to achieve the maximum performance. It has been made based on a viewpoint of solar chimney design that the maximum effect with lower material cost is achieved under this cavity gap [21], or the stack effect that the stack effect is maximum when the cavity gap is within this range [76, 82]. However, the growth ratio of airflow rate was found to be decreasing when the cavity gap increases from 0.15 m to 0.3 m [83].

The value of 0.2-0.3 m may not be applicable to all the configurations. This is because the optimum value is dependent on other factors as well. Spencer [69] indicated that the optimum cavity gap is dependent on the size of inlet areas and chimney height, but not solar radiation. A numerical study [84] found that there existed an optimum cavity gap to maximise buoyancy-induced flow rate, which is between 0.55-0.6 m for a 6.0 m high solar chimney. Another numerical study [85] indicated that it is equal to 0.4 m for a 2 m high solar chimney under the most of the cases except 90°. Based on numerical modelling, Thong et al. [86] stated that a 0.14 m air gap is optimal for the natural ventilation with higher inclination angles. Miyazaki et al. [87] mentioned that the exist of optimum cavity gap during daytime is dependent on the radiative cooling load, which is 2.5 cm under a radiative cooling load of 30 W/m^2.

A wider air gap of solar chimney contributed to higher airflow, which was more significantly influential on solar chimney than inlet size [88]. Bassiouny and Koura [77] obtained the same result that after increasing air gap and inlet size three times, the air change per hour improves almost 25% from the bigger air gap comparing to only 11% from the increased inlet size. A parametric study by Khanal and Lei [26] indicated that the performance of a wall solar chimney is more sensitive to the air gap than the inlet height. However, a numerical study [71] indicated that other influencing factors such as solar absorptance, chimney height and solar transmittance turn out to play more important role on the ventilation improvement when comparing to the air gap.

3.3 Inlet and outlet areas

Inlet and outlet areas are determining factors for air entrance and escape. For a roof solar chimney, the inlet and outlet areas of most previous test rigs are equal to the area of horizontal cross section of the cavity, as shown in Fig. 1(d). This is because these test rigs are in a form of box, consisting of two groups of parallel panels [42, 59, 60]. Under this circumstance, influences of inlet and outlet area on the performance can be partially reflected by cavity gap. This trend is not applicable to some wall solar chimneys with vertical inlet and outlet located in glazing wall or side-wall, as shown in Fig. 1(a).

Within a certain range of cavity gap, both inlet and outlet areas show positive influences on solar chimney performance. An analytical analysis by Bassiouny and Koura [77] concluded that increasing inlet size three times can improve air changes per hour by almost 11%. Another experimental study [69] showed that the ventilation rate increases with a bigger inlet area. Specifically, with a moderate cavity gap, the effect of inlet area on the ventilation flow rate was more significant than that from room opening. However, with a small cavity gap, friction losses in a solar chimney become more critical to the reduction of the flow rate. This phenomenon was also confirmed by Gan [62] that the mass flow rate was found increasing with the inlet height when the cavity gap increases to 0.3 m or 0.5 m, but limited effect was noticed with a cavity gap of 0.1 m.

The effects of inlet and outlet area on the performance are also dependent on other factors. A numerical study [89] showed that for a given chimney geometry, airflow rate can be promoted by a higher chimney cavity, only when its cross sectional area is less than a critical value. This is because the cross section area has a strong effect on transitional and/or turbulent convective heat transfer in an enclosure. Another numerical study [90] suggested that the optimum ratio between cavity height and inlet width is about 20/3 for the Trombe wall. However, the position of air inlet showed limited effects on the air velocity, although the region near to the solar chimney's inlet showed an increase in air speed but was damped when the air speed was averaged across the plane [91]. Outlet port located near the ceiling could result in a more uniform temperature distribution inside building [92].

An equal area for inlet and outlet is beneficial to the improvement of the performance. Based on CFD modelling [89], optimized airflow rate can be gained with equal outlet and inlet areas. For unequal openings, the outlet area plays a more importance role than inlet area. This can be proved by the experiments taken by Susanti et al. [35]. Fig. 3 shows the influence of outlet (A_{out}) and inlet (A_{in}) ratio on volumetric flow rate [56]. Cases with 312/14, 312/8 and 312/4 show higher airflow than those with 14/312, 8/312 and 4/312 opening ratios. This trend is more obvious with a small inlet or outlet.

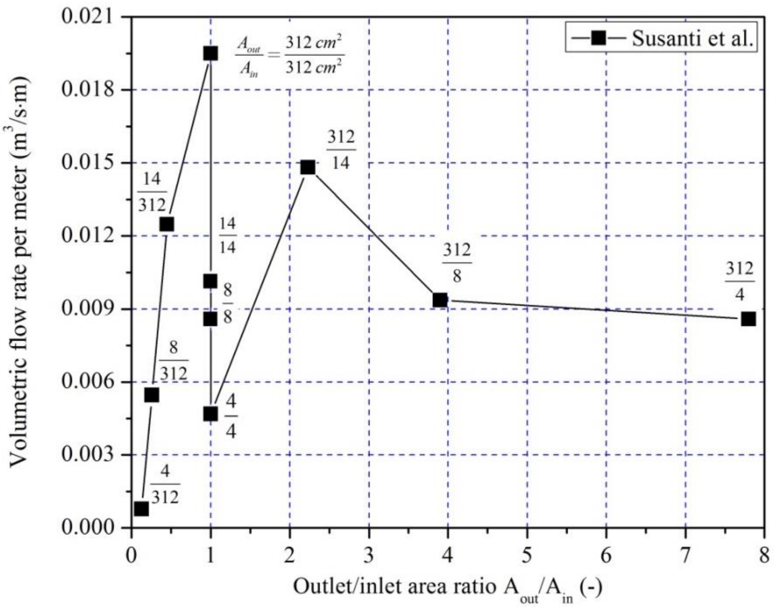


Fig. 3 Influence of outlet/inlet area ratio on volumetric flow rate per meter [56]

Based on numerical modelling, a relationship between airflow rate and inlet/outlet areas was obtained for wall solar chimney by Shi and Zhang [55]:

$$V = 0.16 - 0.009A_r - 0.025A_r^{-1}, \quad A_r = A_{in}/A_{out} \tag{6}$$

3.4 Height/gap ratio

Height/gap ratio usually refers to the ratio between cavity height and gap for wall solar chimney, which is the ratio between cavity length and air gap for roof solar chimney. Influences of cavity height and air gap on the performance have been reviewed in Sections 3.1 and 3.2, respectively. The effects of height/gap ratio on the performance are then determined by the combination of these two parameters.

Previous studies have been largely taken to obtain the optimum height/gap ratio. A optimum ratio of 10 was obtained from both numerical modelling [89] and experiments [93]. Wang et al. [90] indicated based on numerical modelling that in most of the simulated cases the optimum ratio is 10, which was found to be dependent on inlet design and independent of solar radiation. For roof solar chimney, Du et al. [73] obtained based on numerical modelling that the optimal ratio between chimney length and cavity gap is 12. For solar collector above the roof, the ratio between cavity length and hydraulic diameter must be greater than 15 to ensure a developed flow, and the ratio between stack height and width should be less than 7 if the airflow within the solar chimney is two-dimensional [91].

The optimum ratio may not be applicable to other configurations. This is because they were obtained based on one configuration and the optimum ratio could be affected by other factors. Zamora and Kaiser [94] obtained numerically that the higher value of Rayleigh number, the lower value of the optimum ratio. The ratio was also found to be determined by inlet area and solar radiation [90]. An numerical study [95] indicated a optimum ratio of 2 for those vertical roof solar chimneys with both ends open, compared with the usual ratio of 10 for the Trombe wall. Other factors may affect the optimum ratio, such as cavity materials, inclination angle, opening, thermal insulation, even the external wind. However, no related study has been found in the literature.

Some studies claimed no optimum ratio for some chimney configurations. The ratio on ventilation was studied by Mathur et al. [49] with nine different combinations of absorber height and air gap width for a reduced-scale solar chimney. It was known that air flow rate increases with a higher ratio. However, the most suitable aspect ratio was not reported. Another experimental study [42] showed when changing air gap and maintaining all other conditions, the airflow rate increases continuously with a bigger chimney gap, even to a ratio of 5:2 – no optimum gap has been found as well.

Some studies have focused on solar collector. It is known that the airflow rate increases under a higher ratio between absorber height and the air gap [96]. Afonso and Oliveira [31] suggested that for a given solar collection area, the design is better to be with a larger cavity gap and a smaller height.

3.5 Recommendations related to design

Four influencing factors on solar chimney performance were analysed in terms of its configuration, including height, cavity gap, inlet and outlet areas, and height/gap ratio. Several recommendations are provided to guide the designs:

- A possibly high cavity is beneficial to enhance its performance, which is due to the increased pressure difference and heat gain. A power function is shown between airflow rate and cavity height with an exponent between 1/2 and 2/3. It is also applicable to multiple storeys building that a high cavity through all the floors with a jointed outlet at the top can improve the performance;
- An appropriate cavity gap is significant to the performance of a solar chimney. This is because the airflow rate not always increases with a bigger cavity gap due to reverse flow under uneven heating of air inside the cavity. An optimum cavity gap of 0.2-0.3 m is applicable to most of the cases, but not all the cases as it is dependent on other factors as well, such as inlet area, chimney height, and inclination angle;
- Bigger inlet and outlet are suggested within a certain range. An equal area for inlet and outlet is a good way to improve the performance of a solar chimney. For unequal openings, increasing outlet area seems to be more efficient comparing to the inlet; and
- A ratio of around 10 is suggested between cavity height and gap for most of the cases. Optimum ratio is also dependent on other factors, such as air velocity, cavity material, inclination angle, and thermal insulation.

4. Influences of installation conditions

4.1 Inclination angle

Inclination angle of a solar chimney generally refers to the angle between chimney cavity and the horizontal, which 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(d). The inclination angle for a wall solar chimney is considered as 90°.

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° [1, 10, 36, 42, 60, 96]. It was indicated that solar chimney with an inclination angle around 45° is about 45% higher than that of a vertical chimney when other conditions are identical [42, 60], which can be explained by the lowest pressure loss. Zhai et al. [36] explained this by the balance between stack pressure and convective heat transfer coefficient. Theoretically, a higher inclination angle can cause a high stack pressure inside the chimney cavity, which also can result in decreased convective heat transfer. So the inclination angle of 45° is a balance between these two to achieve the maximum natural ventilation.

For roof solar chimney, previous studies indicated that the optimum inclination angle is not equal to that with the maximum solar radiation. Based on an analytical model, Sakonidou et al. [97] obtained that maximum air flow is achieved in a rather narrow range of 65-76° in Greece, while the angle with the maximum solar radiation varies between 12° and 44°. Prasad and Chandra [98] observed a similar phenomenon in India that the optimum inclination angle and the angle which receives the maximum solar radiation are 53-76° and 0-55°, respectively. Above studies showed a similar result that the optimum inclination angle is higher than that with the maximum solar radiation. It means the optimum inclination angle is not only determined by solar radiation, but also other designing factors.

Based on experimental data from different test rigs, Shi et al. [56] noticed two optimum inclination angles (45º and 60º) are usually obtained from experiments in the literature, while these data should show a symmetric distribution around the exact optimum inclination angle. It was then hypothesized that the exact optimum inclination angle would not coincidently be 45º or 60º as previous experimental tests have been done with an interval of 15º. It could be an angle between 45º and 60º. A relationship was given based on the hypothesis between the volumetric ventilation rate and inclination angle for roof solar chimney:

$$V \propto \left(\sin\theta'\right)^{1/3}, \quad \theta' = \begin{cases} \theta, & \theta \le 52.5^\circ \\ 105-\theta, & \theta > 52.5^\circ \end{cases} \tag{7}$$

Latitude was also found to be an important factor related to the optimum inclination angle. Based on a mathematical model, optimum inclination angles for roof solar chimney were obtained by Mathur et al. [54] for latitudes within 0-65°. It was known that the optimum inclination angle is between 45-60°, while for latitude within 20-30° the optimum inclination is 45°, and it increase a little bit for latitudes approach the two sides. Another analytical study by Bassiouny and Korah [99] obtained that the optimum airflow rate was achieved when the inclination is between 45-70° for a latitude of 28.4°. Harris and Helwig [22] stated based on numerical modelling that for a south-facing chimney, an inclination angle of 67.5° is optimum for Edinburgh with a latitude of 52°, giving 11% greater efficiency than the vertical chimney.

Besides the latitude, other factors also show influences on the optimum inclination angle. AboulNage and Abdrabboh [70] obtained the optimum inclination angle of 25° with an air gap of 0.25 m. An experimental study [100] showed that the optimum length of a roof solar collector should be less than 1 m with inclination angle equal to 30°.

Some special configurations have also been analysed. For example, the cavity is constructed by an inclined absorber wall or glazing wall. In a study taken by Khanal and Lei [101], this configuration is called inclined passive wall solar chimney, as shown in Fig. 4(a). Inclination angles of 84-90° from the horizontal were investigated and an optimum inclination angle of 86° was obtained based on simulation. Another numerical study [102] indicated from the thermal point of view that a straight chimney in place of a convergent does not lead to substantial differences, as shown in Fig. 4(b). However, the converging cavity decreases from a maximum speed of 0.92 at straight duct to 0.88 m/s, showing a reduction of approximately 5%, while the mass flow is reduced by about 20%, from 0.227 kg/s to 0.185 kg/s.

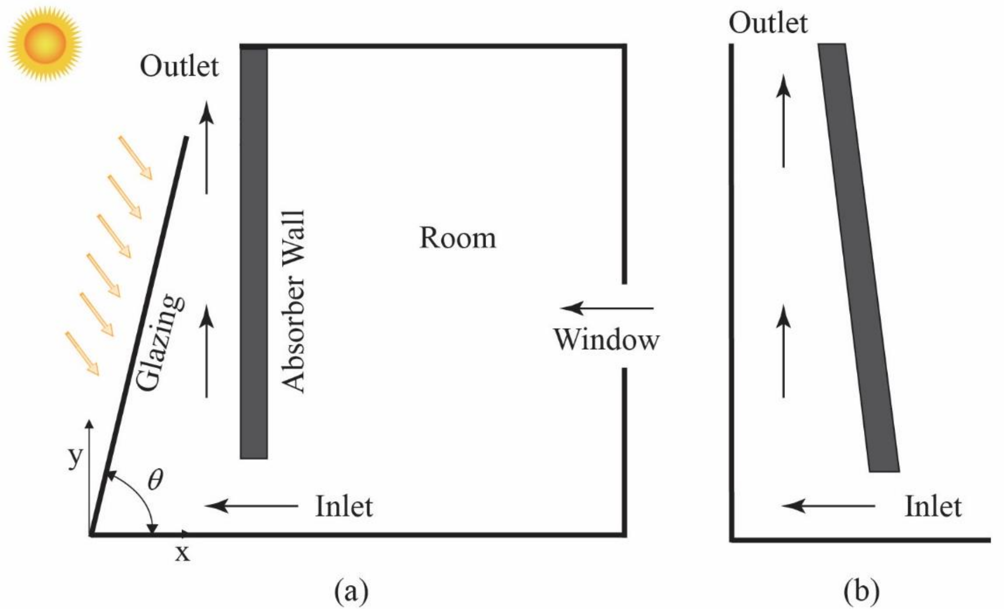


Fig. 4 A schematic of: (a) inclined passive wall solar chimney; and (b) solar chimney with a converging cavity. Figures were revised from References [101, 102].

4.2 Opening of the room

Opening usually refers to window, skylight, door and others connected the room with other room or outdoor environment which can bring in fresh air. The location of these openings can be in a wall (e.g. windows) or on the ceiling (e.g. skylight). The function of these openings is to promote the circle of airflow, such as air exhaust or supply, which are useful to promote natural ventilation and heat exchange in building.

Efforts have been made to optimize opening design for a solar chimney. Based on a factorial design analysis, three most important parameters, highly related to its performance, are door status, extract fan and stack size [103]. It was known that in hot climate, the concept of solar chimney can be utilized by making minor modifications in existing windows to have the advantages of keeping away the solar heat and enhancing the indoor ventilation [41].

Relationship between optimum opening and other influencing factors has been addressed previously. The optimum opening width was found relating to chimney height and air gap, which increases with a bigger air gap width and chimney height [90]. Priyadarsini et al. [104] indicated based on experiments that even though the airflow velocity is much higher when doors are closed, they are more or less localized, but the velocity increase is distributed more evenly when the doors are open.

It should be noticed that not always big opening favours the performance of solar chimney. Ding et al. [68] based on a prototype building for the test indicated that the growth rate of air change rate decreases sharply with an over 16 m^2 opening area between occupant space and double-skin space, and an opening area of 16 m^2 (2 m^2 each floor) is considered reasonable to obtain preferable performance.

Based on numerical modelling, Shi and Zhang [55] indicated that a skylight shows a slightly higher volume rate than other openings such as window and door. A relationship between the volume flow rate and opening area (A_{open}) was obtained then,

$$V = \frac{A_{open}}{0.65 + 5.2A_{open}} \tag{8}$$

Some innovative measures could be helpful under some circumstances. For example, a combination of room opening and solar chimney was utilized, such as window solar chimney, shown in Fig. 1(c). The possibilities of using windows as solar chimneys was confirmed when an up to 0.24 m/s air flow was experimentally recorded [41]. For glazed solar chimney wall under tropical climatic conditions, such as in Thailand, with a clear glass of 6 mm thickness, velocity field measurement indicated that the induced airflow rate was about 0.13-0.28 m^3/s [30]. It was also confirmed that the glazed solar chimney is highly suitable for hot areas, as it can decrease the indoor heat gain through glass wall by enhancing the air circulation, which is helpful to promote the thermal comfort of residents.

4.3 Solar collector

Solar collector can be in different styles coupled with roof: vertical solar collector (Fig. 1(e)) or solar collector installed along the inclined roof (Fig. 1(d)). Fig. 1(f) shows a combination of these two that both the inclined duct and vertical solar collectors can absorb solar radiation. Both types of solar collectors need to have good optical performance to increase the temperature of inside air by absorbing as much heat as possible [105].

Solar collector plate affects the performance of solar chimney as well. El-Sawi et al. [106] tested three types of solar collectors, including flat, v-grooved and chevron pattern absorbers, as shown in Fig. 5. The chevron pattern absorber was found to have the best performance, reaching up to 20% enhancement of thermal efficiency and an increase of 10 °C in outlet temperature under some flow rates. Mathur et al. [107] also studied four types of solar chimney experimentally to confirm their viability. It was known that a cylindrical solar chimney could be easily integrated to the existing building façade than the other types, and the airflow rate could be increased by 15.94% with 45° inclination angle under a solar radiation of 949.53 W/m^2. It was also indicated that the cylindrical chimney covered with a transparent sheet can increase the ventilation rate by 36.85% when comparing with bare one.

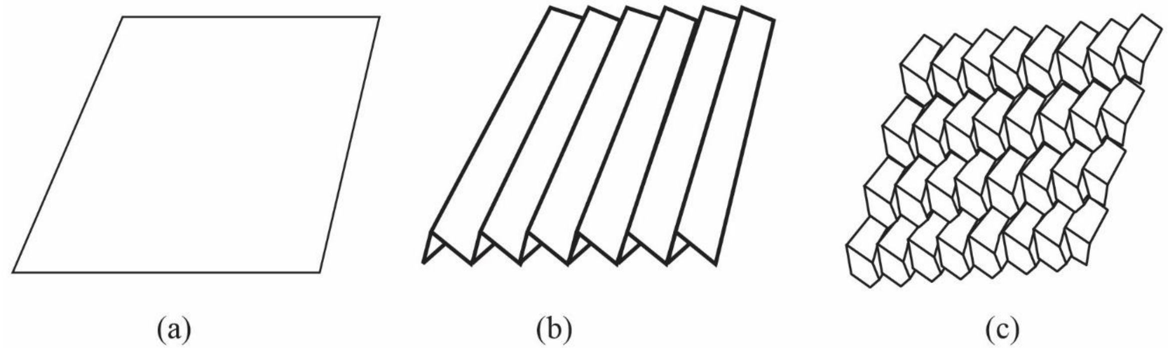
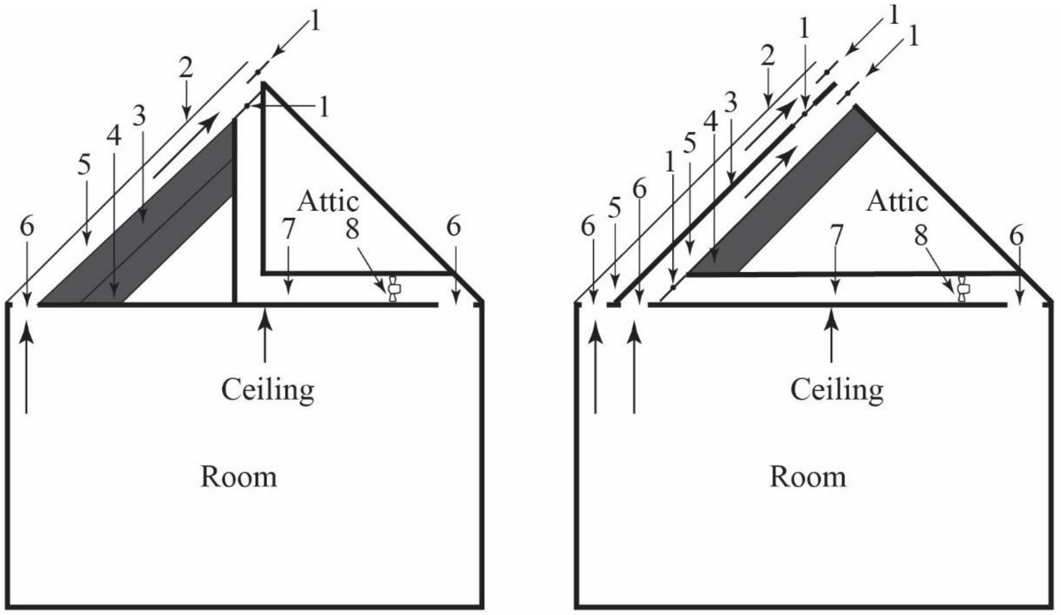


Fig. 5 Three types of solar absorber plates were used for roof solar chimney: (a) flat; (b) V-grooved; and (c) chevron pattern. Figures were revised from Reference [106].

Size of solar collector is an important factor for solar chimney. An analytical study [72] showed that average velocity, average mass flow rate and performance increase gradually after increasing the area of solar collector. Experimental results from a reduced-scale model stated that the ventilation rate rises with the increased ratio between absorber height and cavity gap [49]. Another experiment by Al-Kayiem et al. [108] obtained that the roof solar chimney with additional vertical absorber at the roof shows an enhanced performance of 1.2-7.6%.

Configuration of solar collector has been investigated previously. Two types of roof solar collectors, namely single pass (Fig. 6(a)) and double pass (Fig. 6(b)), were investigated by Zhai et al. [109] numerically. It was known that the instantaneous efficiency of the double pass is higher than that the other by 10% averagely. The air mass flow rate for the double pass can be improved under most cases, indicating that the double pass is superior to the single pass in terms of both heating and cooling. A single-glazed solar collector with corrugated aluminium absorber (insulated at the back) normally can provide an average temperature rise of 25 °C under 900 W/m^2 solar radiation[110]. A double-glazed collector with a flat absorber, operated in forced convection model at a similar airflow rate of 72 m^3/(h.m^2), can deliver a temperature rise of about 29 °C under 915 W/m^2 solar radiation [111].



(a) (b)

Fig. 6 Structures of single pass (a) and double pass (b) roof solar collector under natural ventilation model: 1 – damper; 2 – glass cover; 3 – absorber plate; 4 – insulation plate; 5 – air channel; 6 – tuyere; 7 – air duct; and 8 – fan. Figures were revised from Reference [109].

4.4 Recommendations related to design

In this section, three influencing factors were analysed regarding the installation conditions of solar chimney, including inclination angle, opening of the room, and solar collector. Several suggestions can be made to design a solar chimney:

- Inclination angle is the key factor to roof solar chimney, and an optimum inclination angle of 45-60° is suggested considering the latitude of the building. The optimum angle should be considered with a balance between stack pressure and convective heat transfer. Due to this reason, for a solar chimney at a specific location, the optimum inclination angle is higher than the angle receiving the maximum solar radiation;
- A bigger opening is not always worthwhile for a room to enhance the performance of a solar chimney, and the growth rate could decrease when approaching a value. The position of the opening seems to be not so significant, while skylight shows a slightly better performance comparing to window and door; and
- The purpose of solar collector is to gain as much heat as possible from the solar radiation. Therefore, a design of favouring the heat gain can improve the performance, such as increasing the area of collector plate and using materials with high absorptivity and low thermal conductivity.

5. Influences of material usages

5.1 Type of glazing

Glazing is largely used in both wall and roof solar chimney, as shown in Fig. 1(a) and Fig. 1(d). It aims to enhance thermal buoyancy inside the cavity through the heating processes. Several properties of glazing are important to solar chimney performance, such as transmissvity, reflectivity and absorptivity. An experimental study by Lee et al. [1] indicated that the transmissivity of glazing is important for a solar chimney, and a high value can increase the outlet temperature and also the performance. The influences of the transmissivity of chimney glazing on temperature rise were found more obvious than those from reflectivity and absorptivity.

A theoretical analysis [112] showed that the surface temperature of glazing is lower than the mean air temperature inside a chimney cavity under a solar radiation of 400 W/m^2, while this trend turns to an opposite when radiation is rising. In addition, double glazing shows its advantage in enhancing the performance. Hatami and Bahadorinejad [113] investigated six cases, while the two cases are equipped with one glass cover for air heaters and the other four cases are with two glass covers. Maximum efficiency was obtained when the air heaters had two glass covers and the air could flow through all cavities. For winter usage, triple glazing was suggested as single and double glazing are inadequate for solar chimney due to possible condensation or downdraught [114].

Although double glazing shows its advantages, it seems to be a good choice for winter heating but not for solo summer cooling considering the cost. When the double glazing was applied to the Trombe wall in summer, the airflow rates was found to increase by 10-17% [62]. However, Harris and Helwig [22] indicated that the double glazing utilized for winter heating (i.e. Trombe-wall type) would be greatly useful, but for solo cooling for summer conditions the extra cost is probably not worthwhile.

5.2 Materials of solar absorber

Materials have been utilized in solar chimney for several functions, such as thermal insulation, storage and absorption. For roof solar chimney shown in Fig. 1(d), a thermal storage layer with phase change material under the cavity is utilized to absorb as much heat as possible from the hot air in chimney cavity. The phase change material absorb external heat companied with phase change, for example, from solid to liquid [115]. It can release the absorbed heat at a later stage when the phase changes back. The bottom layer of insulation is aiming to minimize the heat loss for the storage layer.

Solar chimney is designed to enhance ventilation by maximizing the obtained heat from the Sun [64]. A numerical study [71] indicated that after the increase of solar transmittance from 0.25 to 0.92, airflow rate can be increased by 40%, 38% and 36% in three typical United States cities. A longer cavity and also the absorber plate with a black-polished surface could obviously enhance the air temperature at the outlet and the solar chimney performance [1]. However, for this case, the improvement was not evident when the length exceeds approximately 4.0 m, which is due to the dropped efficiency.

Absorptivity of solar collector plays an important role for roof solar chimney. Lee and Strand [71] addressed the effects from its absorptivity, and showed an up to 57% enhancement in air flow rate when the solar absorptance rises from 0.25 to 1.0. This is because of the increased surface temperature of the absorber wall under the condition. It was then suggested that the highest absorptance can he helpful to optimize solar chimney performance. Pillai and Agarwal [116] obtained a linear relationship between the absorptance and the efficiency of solar collector with a more than 0.8 absorptance.

The significance of a better absorptivity was also confirmed by Liu et al. [117]. It was indicated that a V-groove collector could be with considerably better performance than that of flat-plate collector. During the solar chimney design, it is essential to:

- Utilize a small V-groove absorber for the related collector;
- Keep a small gap for the flat-plate collector between absorber and bottom plate;
- Use selected coatings with a very high absorber also the glass cover;
- Maintain no less than 0.1 $kg/m^2 \cdot s$ airflow rate; and
- Enable an airflow entry with its temperature similar to the room temperature.

Emissivity of the solar absorber is also important to the performance. As for many practical materials their emissivity is located in a range of 0.7-0.9, it is quite straightforward that the heat transfer by radiation cannot be ignored for a solar chimney [118]. A numerical study [26] stated that airflow rate is enhanced with a higher surface emissivity, showing an up to 59% enhance when it rises from 0 to 0.9.

However, comparing to emissivity, solar absorptivity seems to play a more important role. Leon and Kumar [119] has addressed the effects of three parameters, including solar radiation, thermal emissivity and solar absorptivity, on solar collector performance. It was known that the absorptivity has the largest influence on the efficiency when comparing to the emissivity. Pavlou et al. [120] mentioned that the surface of a collector can be designed with the possibly highest ratio between absorptance and emittance. However, it was also reported by Pavlou et al. [120] that the influences of the absorptivity of external surface (e.g. glazing) on the performance can be ignored.

New concepts have also been initiated following the principles, such as absorbing as much solar radiation as possible and storing them appropriately. A metallic solar wall (MSW) was investigated through a full-scale model with one room in Thailand with tropical climates [47]. The MSW contains black metallic plate, a glass cover, air gap, and an insulator (by microfiber and plywood). It was shown that a 2 m high MSW with an cavity gap of 0.145 m could bring in an up to 0.02 kg/s airflow rate for a 2.68 m high and 11.55 m^2 house.

5.3 Thermal insulation

Mass wall is one of the very important components for a thermal storage wall like the Trombe wall. Through it the solar heat can be stored and transmitted into a building. Therefore, the related material is critical for a mass wall [121]. A study [62] mentioned that about 40% of the gained heat by a wall would be transferred to the adjacent living room by thermal conduction through a 0.3 m thick non-insulated wall. The design of the emissivity of back wall should be possible low to reduce the heat losses through radiation processes, and a low-e coating could increase the airflow rate by 10%, stated by Harris and Helwig [22].

Thermal insulation shows a relatively more importance than many other factors. For example, an experimental study [122] indicated that decreasing the resistance of heat transfer in the cavity play the most important role on thermal efficiency enhancement, when comparing to other four parameters such as optical properties of glazing cover, stagnant air layer height , absorber plate surface emissivity, and the conductive resistance of back plate. It follows by the designs of stagnant air layer adjustment and enhanced transmittance of the glazing cover. Several attempts were found negligible, such as increasing the thermal conductivity of the back plate or reducing the emittance of the absorber plate.

Optimum thickness of the insulation wall was also suggested in previous studies. A numerical study [31] suggested that a thickness of 5 cm insulation wall is enough and no obvious enhancement can be observed with above 10 cm thickness. The study also showed that it is fundamental to use outside insulation in brick wall to take advantage of solar gains, and thermal efficiency is reduced by more than 60% if outside insulation is not used. The optimum thickness for a storage wall is much dependent on the use pattern of a building. A thin wall is enough for daytime usage, but for night time a thick wall will be preferable. A 5 cm thick insulation is considered enough and optimum.

Wall thickness design may be affected by other factors. The influences of the thickness of a wall was found insignificant on the performance under a low Reynolds number; but it is significant under a high Reynolds number [123]. Miyazaki et al. [21] investigated the influences of internal insulated wall in a solar chimney. It was known that the ventilation rate can be enhanced by improving the inner wall with a higher insulation level.

5.4 Recommendations related to design

Regarding the material usage, three influencing factors were analysed on addressing solar chimney performance, including type of glazing, materials of solar absorber and thermal insulation. Recommendations are made to benefit the design of solar chimney:

- Regarding the selection of glazing, properties of transmissivity, reflectivity and absorptivity are important to the performance of a solar chimney, while transmissivity plays more important role than the other two. Double glazing shows its advantage in enhancing the performance of a solar chimney. However, when considering the cost, it seems to be a good choice for winter heating but not solo summer cooling;

- The material of solar collector is highly relevant to the solar chimney performance. Absorptivity and emissivity are two of the important properties, while absorptivity seems to be more important than the emissivity. Several measures can enhance the performance during the design of a solar chimney, such as thermal storage layer and absorber plate with black-polished surface; and
- Thermal insulation of cavity wall is significant to improve the solar chimney performance. A thickness of 5 cm insulation wall is suggested when considering the cost as it provides no significant drop of the performance when comparing to the insulation wall with over 10 cm thickness.

6. Influences of environment

6.1 Solar radiation

The energy from solar radiation is able to drive the air inside the chimney cavity. It can bring in adequate air movement under the availability of solar radiation [124]. A theoretical analysis [70] indicated that an evaporative cooling cavity system equipped solar chimney can enable a great indoor condition during daytime even with a low solar radiation of 200 W/m^2. A roof solar chimney alone has been proved to induce 0.81 m^3/s air flow rate under an average radiation intensity of 850 W/m^2. Under a solar radiation up to 650 W/m^2, experimental results confirmed an obtained air velocity of 0.25-0.39 m/s[50].

It is quite sure that high solar radiation can enhance the solar chimney performance. A numerical study [34] showed that both the ventilation efficiency and airflow rate increase under a higher solar radiation. Manca et al. [102] specified the influences of solar radiation on wall temperature, velocity and airflow rate. After doubling the solar radiation from 300 to 600 W/m^2, an almost 30% increase rate can be observed at the outlet, companied with an almost 30% increase of the maximum velocity, and about 10% enhancement of the maximum temperature on the heated wall. Bansal et al. [64] obtained that 100 m^3/h and 350 m^3/h is possible for a solar chimney with a surface area of 2.25 m^2 when it is put under solar radiation of 100 W/m^2 and 1,000 W/m^2, respectively.

Quantitative investigations have been conducted to address the influence of solar radiation on the performance. Bassiouny and Koura [77] obtained a relationship between the average temperature from the absorption of solar heat and average air outlet velocity, indicating a factor of 2.25 increase of the maximum absorbed temperature with a factor of 5 rise of solar radiation. Another experimental study taken by Chen et al. [42] showed that the ventilation flow rate can be rised by about 38% with an increase of heat flux from 200 to 600 W/m^2. Mathur et al. [49] obtained a linear relationship between the ventilation rate with solar radiation.

Burek et al. [38] obtained through experiment that the airflow rate of the cavity is related to the absorbed heat:

$$V \propto Q^{0.572} \tag{9}$$

Based on those experimental data from different experimental setups, Shi et al. [56] also presented a similar result regarding the influence of heat input,

$$V \propto q^{1/2} \tag{10}$$

Although the air temperature at outlet can be slightly increased under a higher solar radiation, the efficiency of the system is not obvious improved. A compromised operation status may happen at a relatively bigger airflow rate when the solar chimney is operated under a higher solar radiation. An experimental study [1] showed that the efficiency of a solar chimney (1.6 m high, 0.6 m wide, and 0.08 m thick) only increase from 20% to 24% when solar radiation rises from 340 to 960 W/m^2. Another theoretical study [125] also indicated that the maximum instantaneous efficiency for a solar chimney (1.95 m high, 1.75 m wide, and 0.24 m thick) increases from 28% to 37% when solar radiation rises from 100 to 700 W/m^2.

6.2 External wind

External wind shows significant influence on the solar chimney performance. Arce et al. [80] concluded that the ventilation rate is significantly influenced by the pressure difference between openings with wind velocity and thermal gradients. A numerical study [126] also indicated that the wind velocity is significant to the ventilation rate of a building, besides the opening geometry and the angle of wind flow. Another experimental study [127] showed that solar chimney can bring in significant portion of natural ventilation by 1.13-2.26 of air change per hour even without considering the effect from wind, accounting for 7.5-15.1% compared to the high air change per hour with wind effect [128, 129].

In a naturally ventilated building, external wind is still one of the most critical factor to determine the performance [103]. Experimental study by Tan and Wong [32, 130] showed that a no less than 2 m/s air speed can improve the air speed within the chimney cavity, while whatever air speeds are observed capable of improving the air speed inside the tested class room. However, with a solar radiation higher than 700 W/m^2, the importance of the external air speed is reduced. Al-Kayiem et al. [72] obtained a similar result when the external wind velocity rises from 1.5 to 6 m/s, reducing the performance of the system by 25% at a solar radiation of 900 W/m^2.

Solar-wind tower is also used to enhance natural ventilation. The concept has been confirmed by Nouanegue et al. [123] numerically, and they considered a case with mixed ventilation: forced convection in the tower system due to the negative pressure raised at the outlet of the tower under both the Venturi and buoyancy effects. It was known that the wall thickness showed less influence on the performance when comparing to the other factors. Bansal et al. [131] adopted a similar configuration, where the solar chimney was installed at the exit of the outlet apertures of room, considering an ignorablestack effect inside.

Due to random wind profiles from outdoor, solar chimney design can be taken without considering the effects from external wind, as it will underestimate the real performance [31]. A theoretical study by Dai et al. [132] indicated that if without considering the wind effect, airflow rate can be designed considering solar radiation, ambient temperature as well as the cavity configuration.

6.3 Other climatic conditions

As solar chimney performance highly depends on the availability of solar radiation in a location and also the cavity height, it is then critical to consider the relevant climatic conditions when designing the solar chimney [71]. May other factors should be considered as well, including building orientation, location, climate, room size and internal heat absorption [22].

Although solar chimney is often questioned under insufficient solar radiation, some studies have confirmed its applicability in this area with an increased absorber area. Drori et al. [133] indicated that the solar chimney is also able to ventilate small size homes even with a availability of low solar radiation (around 50-60 W/m^2) after increasing the absorber area and using two inner partitions. Another experimental study [134] showed a well-performed solar chimney even during cool days under low solar radiation in hot and humid climate. It was known that even with a low solar radiation, the solar chimney can bring in an average air speed of 1.5 and 0.4 m/s within the cavity and the classroom at the first level, respectively, after interconnecting thermal stack in a hall. A combined experimental and numerical study by Letan et al. [135] demonstrated that even at low solar irradiation fluxes, ventilation of a five-storey building was achieved cooling in summer and heating in winter with extended surface area of the absorber duct.

There is no common agreement for night usages of solar chimney. Kaneko et al. [136] mentioned that the solar chimney is not capable of working under night time because of the low heat gain. However, Charvat et al. [137] indicated that it can be used for night ventilation/cooling when including a heat storage mass. Marti-Herrero and Heras-Celemin [138] proposed a 0.24 m thick concrete wall for night usage that a peak temperature can be observed even 2 hours after the ambient temperature, expanding the duration of high temperature. Possibility of using solar chimney was also confirmed for Mediterranean conditions by Koronakis [139] and Arce et al. [80]. The roof solar chimney showed a promising way of ventilating a house throughout both the day and night, without major changes in the house [140].

To promote the usage of solar chimney during night or cooling period, several approaches have been utilized in the literature. An experimental study taken by Sharma et al. [141] showed that of the usage of PCM is beneficial, showing a constant ventilation rate of 155 m^3/h even during evening and night periods. A numerical study [142] showed that the composite Trombe wall shows a enhanced performance after using it in cold and/or cloudy climatic conditions. The solar chimney with a built-in latent heat storage material has been analysed by Kaneko et al. [136] for the prolongation of evening/night time ventilation.

6.4 Recommendation related to design

Environmental factors affecting solar chimney include solar radiation, external wind and other climatic conditions. According to the mechanisms of solar chimney, it is quite sure that high solar radiation can enhance its performance, and the volumetric flow rate shows a 0.5-power function with solar radiation. If designing a solar chimney, measures are needed to be taken to absorb as much solar radiation as possible. Although the external wind shows significant influence on the performance, solar chimney deisgn can be taken without considering the effects from external wind because of its random profile. Other climatic conditions, such as location and building orientation, are important to the design of a solar chimney. The designing principle is the same with solar radiation, namely absorbing as much heat as possible.

7. Conclusions

This paper reviewed the influences of four types of influencing factors on the performance of solar chimney, including configuration, installation conditions, material usages, and environment. Several conclusions can be addressed:

- Statistical analysis of previous experimental studies showed that the overall range of test parameters is still limited which requires more future experiments, especially on material usages, environmental factors, chimney height, and inlet/outlet ratio. The overall test ranges on solar chimney is: inclination angle (10-90º), cavity gap (0.02-1.2 m), height (0.521-2.07 m), height/gap ratio (1.7-103.5), inlet area (0.019-1.2 m^2), outlet area (0.016-1.5 m^2), inlet/outlet ratio (0.093-23.0), and radiation heat (20-1,057 W/m^2). Four types of mathematical models were developed for performance prediction of solar chimney, as seen in Table 2 they include predictions based on single parameter, air temperature, air density or external solar radiation;

- Experimental airflow rate from various test rigs showed a good exponential relationship with cavity height with an exponent of 2/3. Optimum airflow rate can be obtained under a cavity gap of 0.2-0.3 m and a height/gap ratio of about 10. An equal area for inlet and outlet is beneficial to enhance the performance, and outlet area shows a relatively higher importance than inlet area. These optimum values, like those values shown below, may not be applicable to all the configurations as they are interdependent;

- An optimum inclination angle for roof solar chimney in previous studies located in a range of 45-60º (most of them obtained 45º), which showed dependence on latitude, air gap and chimney height. Optimum opening was found increasing with a bigger air gap and chimney height, but it not always favours the performance of a solar chimney. The type, size and configuration of a solar collector can influence solar chimney performance, which favours chevron pattern absorber, big area and double pass;

- Previous studies suggested double or triple glazing for winter heating, while for solo summer cooling it is not necessary as the additional cost may not be worthwhile. Both the absorptivity and emissivity of solar absorber materials can enhance the performance, while the absorptivity seems to be more important. Insulated wall can enhance the performance of solar chimney, while a thickness of 5 cm insulation wall is considered enough and no obvious improvement can be observed with above 10 cm thickness; and

- Although solar chimney is often questioned under insufficient solar radiation, some studies have confirmed its applicability in this area with an increased absorber area. It was known that the volumetric flow rate increase exponentially with solar radiation with an exponent of around 0.5. Although external wind shows significant influence on the solar chimney performance, its design can be undertaken without considering the effects from the external wind, which could underestimate the related performance.

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