Renewable and Sustainable Energy Reviews 88 (2018) 223–238

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

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

Long Shi[a,*], Guomin Zhang[a], Wei Yang[b], Dongmei Huang[c], Xudong Cheng[d], Sujeeva Setunge[a]

[a] Civil and Infrastructure Engineering Discipline, School of Engineering, RMIT University, Melbourne, VIC 3001, Australia
[b] College of Engineering and Science, Victoria University, Melbourne, VIC 8001, Australia
[c] College of Quality and Safety Engineering, China Jiliang University, Hangzhou, Zhejiang 310018, PR China
[d] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China

ARTICLE INFO

Keywords:
Solar chimney
Configuration
Installation condition
Material usage
Environment
Optimum design

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.

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].

* Corresponding author.
E-mail addresses: shilong@mail.ustc.edu.cn, long.shi@rmit.edu.au (L. Shi).

https://doi.org/10.1016/j.rser.2018.02.033
Received 20 January 2017; Received in revised form 5 September 2017; Accepted 27 February 2018

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 Ref. [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].

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 20–1057 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.