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Experimental study of the prediction of the ventilation flow rate through solar chimney with large gap-to-height ratios

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ABSTRACT

In this study, experiment was carried out with a solar chimney model with large gap-to-height ratios between 0.2 and 0.6. The experimental results show that the existing prediction method available in the literature overpredicts the airflow rate for chimney geometry investigated in this work, especially for vertical solar chimney with large gap-to-height ratios. An improved prediction method, which takes into account the variation of pressure loss coefficient for different flow conditions at the chimney outlet, is presented and compared with the experimental results obtained in this work and available in the literature. It is shown that the improved prediction method are in better agreement with the experiment results than the existing prediction method available in the literature for both narrow and wide chimneys. On the other hand, it is also found that the temperature and velocity distribution of air and airflow rate in chimney are highly dependent on heat flux and chimney gap. Experimental results show that an optimum gap-to-height ratio that maximizes the airflow rate in chimney is around the gap-to-height ratio of 0.5.

1. Introduction

Nowadays, buildings consume roughly 40% of the energy use, reported by Dodoo [1]. In recent years, there has been an increasing interest in promoting the energy savings in buildings. Solar chimney serves as an excellent natural ventilation strategy for reducing buildings consumption. Solar chimney relies on the buoyancy-driven natural convection to induce airflows in a vertical channel or inclined channel. However, solar chimney as a passive ventilation strategy has not been completely understood despite continuous research effort devoted to the topic over an extended period of time, especially large-scale solar chimney, and so their exact performance can seldom be predicted accurately. In the past decade, solar chimney as a passive ventilation strategy has attracted so much attention in various investigations.

The thermal performance of solar chimneys using different geometrical configurations and material has been experimentally studied by different researchers. Hirunlabh et al. [2] studied a metallic solar wall (MSW) as part of a whole building under tropical climatic conditions in Thailand. It was shown that such low cost chimney construction can reduce heat gain significantly in the house to improve the thermal comfort. Arce et al. [3] investigated the thermal performance of a solar chimney with a gap-to-height ratio (Gap/H) of 0.07 under Mediterranean daylight and night time conditions for natural ventilation. Amori and Mohammed [4] investigated the effect of integrating the PCM (Phase Change Material) in solar chimney. Experimental results show that a solar chimney with side entrance gave better thermal performance than that with bottom entrance, while integrating solar chimney with PCM can extend the ventilation period after the sunset.

Natural ventilation on solar chimney by using different designs has also been studied by different researchers. Sanvicente et al. [5] presented an experimental study for both open-ended vertical channel. The experiments focus on the kinematic characteristics of the flow and convective heat transfer at the heated wall. Mathur et al. [6] reported experimentally on a small size solar chimney that the rate of ventilation increases with increase of the ratio between height of absorber and gap between glass and absorber. Ryan et al. [7] reported experiments that focused on the effects of the channel

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height on the flow rate and heat transfer. It was shown that the channel height has an additional positive effect, independent of the gap-to-height ratio. Heat transfer experiments reported by Lai et al. [8] were carried out for different air gap and different inclined angles. The experimental results showed that the optimal air gap is around the sum of both chimney walls' thermal boundary layer thickness.

The thermal performance of solar chimneys was also investigated numerically by other researches. Gan [9] presented results of numerical simulation of airflow and heat transfer in vertical cavities of different heights and widths for ventilation cooling. Two sizes of computational domain were used for simulation. The predicted natural ventilation rate and heat transfer coefficient have been found to depend on not only the cavity size and the intensity and proportion of heat distribution on the cavity walls but also the numerical simulation domain size. Lau et al. [10] investigated numerically the effect of varying inclination angle on the velocity and temperature fields by means of large-eddy simulation (LES). Li et al. [11] discussed numerically the influence of the surface radiation on the laminar airflow induced by natural convection in vertical, asymmetrically-heated channels. Khanal and Lei [12] reported a numerical investigation of flow reversal in a solar chimney over a range of controlling parameters. The reverse flow phenomenon is quantitatively examined by calculating its penetration depth. In order to suppress the reverse flow and enhance ventilation performance, a configuration with an inclined passive wall is proposed as a new design.

It is one of the major tasks for solar chimney designers to predict the airflow rates under given solar radiation intensity and the size of a solar chimney. Considering the heat transfer coefficient along the heated surface and assuming uniform temperature distribution across the same vertical height, Bansal et al. [13,14] obtained air temperature distribution along the chimney channel with uniform wall temperature. By balancing the stack pressure and the pressure loss along the airflow path, airflow rate was obtained. The experiment reported by Sandberg [15] showed that predicted airflow rate was in good agreement with the experimental results for a solar chimney with one wall heated at uniform heat flux and a channel gap-to-height ratio of 1:28. A number of studies of these similar topics are reported subsequently (see for example Aboulnaga [16]; Ong [17]; Martí-Herrero et al. [18]; Bassiouny and Koura [19]).

Above flow rate prediction methods are based on the assumption of uniform temperature distributions across the same vertical height and these prediction methods are applicable to chimney with small gap-to-height ratios. For wide chimneys, Chen et al. [21], Spencer [20], Sandberg and Moshfegh [22] reported that these predictions method can overpredict the airflow rate through the solar chimney. The possible reasons for this overprediction may be duo to two factors. Firstly, the assumption of uniform temperature distribution may no longer be valid for wide chimneys. Secondly, the pressure loss coefficients at the chimney inlet, outlet and along the chimney channel derived from normal forced flows may no longer be adequate for natural ventilation. The occurrence of reverse flows near the chimney outlets for wide chimney may also make especially these theoretical predictions inadequate.

All the studies above were conducted for solar chimney with small to moderate gap-to-height ratios. Solar chimney with large gap-to-height ratios has received very few research attentions. This work aimed to investigate the overprediction of the airflow rate with an existing method for large scale solar chimney with large gap-to-height ratios. An improved prediction method was developed. It was found that the improved prediction method can better the airflow rate prediction in comparison with the existing prediction method available in the literature, especially for solar chimney with large gap-to-height ratios.

2. Analysis

In order to predict the airflow rate inside the solar chimney under given solar radiation intensity and chimney size, all prediction methods available in the existing literature are based on the assumption of uniform air temperature at the same height inside the chimney [13–19]. For the vertical chimney and for small density differences along the chimney, energy balance yields:

$$qhw = Q\rho C_P\left(T_{average} - T_{amb}\right) \tag{1}$$

where h is the height along the chimney, w is the chimney width, q is the heat flux, Q is the airflow rate in the chimney, ρ and c_P are air density and specific heat capacity at ambient temperature, respectively, $T_{average}$ is the average air temperature inside the chimney at the height of h, and $T_{amb}$is the ambient temperature.

The stack pressure, ΔP_s, can be obtained by the following integration:

$$\Delta P_S = \int_0^H \frac{\left(T_{average} - T_{amb}\right)\rho g}{T_{amb}} dh = \frac{\rho BH}{2Q} \tag{2}$$

where B is the buoyancy flux: $B = \frac{gqwH}{\rho c_p T_{amb}}$; H is the chimney height.

The pressure loss along the chimney, ΔP_L, may be expressed as

$$\Delta P_L = c_{in}\frac{\rho(Q/A_{in})^2}{2} + c_{out}\frac{\rho(Q/A_{out})^2}{2} + f\frac{H}{D_h}\frac{\rho(Q/A)^2}{2} \tag{3}$$

where A is the chimney channel cross-sectional area, A_{in} and A_{out} are the inlet and outlet areas; f is the friction factor for the channel wall; c_{in} and c_{out} are the inlet and outlet pressure loss coefficients; and D_h is the hydraulic diameter of the chimney channel.

Assuming that the stack pressure counterbalances completely the pressure loss along the chimney, the airflow rate, Q, for a chimney with a uniform wall heat flux can be obtained as follows:

$$Q = A\left(\frac{B}{2\psi}\right)^{1/3} \tag{4}$$

where

$$\psi = \frac{A}{H}\left[f\frac{H}{2D_h} + \frac{1}{2}\left[c_{in}\left(\frac{A}{A_{in}}\right)^2 + c_{out}\left(\frac{A}{A_{out}}\right)^2\right]\right] \tag{5}$$

The pressure loss coefficients, c_{in} and c_{out} are generally obtained by resorting to the available data for normal forced flows. For a rectangular channel with both ends open and heated on a single wall, Sandberg [15] used $c_{in} = 1.5$, $c_{out} = 1.0$ and $f = 0.056$, respectively.

From the above analysis, it is seen that the airflow rate, based on heat balance analysis and normal forced flow pressure loss coefficient, is mainly determined by two aspects: (a) the stack pressure built up in the chimney and (b) the pressure losses at the inlet, outlet and along the chimney channel. Consequently, correct evaluations of the average air temperature and the pressure coefficients are essential for an accurate prediction of the airflow rate induced by solar chimneys.

3. Experimental

3.1. Experimental set up

Fig. 1 shows the schematic view of the experimental solar chimney. The experimental solar chimney has internal dimensions