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A new analytical model for airflow in solar chimneys based on thermal boundary layers

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ABSTRACT

Solar Chimney is a potentially effective low carbon technique that uses solar energy to heat and cool buildings or to enhance ventilation. Proper design of a solar chimney requires a reliable model to estimate the airflow rate generated by the heat of solar irradiation. Existing analytical models ignore density variations either for the whole channel or across the channel gap. This paper presents a plume model based on energy balances and the thermal boundary theory and thus considered density variations in both horizontal and vertical directions. This plume model, expressed implicitly as a function of heat flux, can be solved easily through simple iterations. The performance of the model was verified by using experimental data in the literature. Results show that the plume model outperformed existing analytical models. Recognizing the challenges in airflow measurement, we suggest that further tests and calibrations of this plume model be done by using more concrete and accurate experimental data. Simple in form, the plume model has its potential in building simulation programs.

1. Introduction

Solar Chimney is a potentially effective low carbon technique that uses solar energy to heat and cool buildings or to enhance ventilation (Maerefat and Haghighi, 2010; Zhai et al., 2011; Tan and Wong, 2012). To properly design a solar chimney, it is necessary to be able to model and predict the airflow rate generated by the solar chimney exposed to solar radiation.

Because stack effect is caused by difference in air density, accurate airflow prediction requires correct representation of density in the chimney. A simple model for solar chimney airflow was developed earlier and has since been used widely (Klote, 1991; Bansal et al., 1993; Ong, 2003; Awbi, 1994; Mathur et al., 2006). The model assumes uniform density distribution (thus uniform temperature) in the channel. The mass flow rate can be expressed in a simple form where the stack effect has been represented by temperature difference between the channel and the reference environment:

$$\dot{m} = \frac{C_d \rho_r A_b}{\sqrt{1 + \left(\frac{A_b}{A_a}\right)^2}} \sqrt{\frac{2gH(T - T_r)}{T_r}} \tag{1}$$

This equation reveals that the mass flow rate is strongly dependent on the temperature of the air in the cavity. Because the temperature is unknown, additional energy balance equations are needed to solve for the mass flow rate. For example, Bansal et al. (1993) proposed an analytical solution for temperature in the cavity. Martí-Herrero and Heras-Celemin (2007) used a more complete energy balance equation including terms of radiative heat transfer between walls. Bassiouny and Koura (2008) proposed a thermal network model to solve for the mean temperature in the chimney. The problem with Eq. (1) is that the discharge coefficient needs to be predetermined. Values between 0.57 and 0.6 have been used in the previous studies. However, it is not known how the size of the chimney (stack height, inlet and outlet shapes) would affect the value.

A more sophisticated model was also proposed to account for the vertical stratification of the density in the chimney (Sandberg and Moshfegh, 1998). Considering the vertical temperature profile, the mass flow rate can be expressed as a cubic root of heat flux:

$$\dot{m} = \eta q^{1/3} \tag{2}$$

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Nomenclature

a	plume width correction coefficient
A	area (m^2)
C_p	specific heat (kJ/kg/K)
C_d	discharge coefficient
d	depth of the channel gap (m)
d_h	hydraulic diameter (m)
e	absolute roughness (m)
f	friction coefficient
g	gravitational acceleration rate (m/s^2)
h	vertical distance along the channel (m)
H	solar chimney height (m)
k	pressure loss coefficient
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
q	heat flux (W/m^2)
R	gas constant (=287.058 J/kg/K for air)
T	temperature (K)
w	width of the channel (m)
x	ratio of plume width to the depth of the channel gap

Greek symbols

β	expansion coefficient (1/K)
ρ	density (kg/m^3)
η	flow coefficient in a channel
δ	thermal boundary layer thickness (m)
λ	heat conductivity (W/m/K)
μ	viscosity (kg/s/m)
γ	temperature weighting coefficient
Pr	Prandtl number
Gr	Grashof number
Ra	Rayleigh number
Re	Reynolds number

Subscript

a	inlet
b	outlet
d	discharge
f	friction
h	channel
H	plume top
r	reference environment
i	inside the channel
p	plume

where the expression of the coefficient η can be theoretically derived by accounting for the frication loss, entrance loss, and other configuration effects. In natural convection dominated solar chimney, these losses can have a significant effect on the flow rate. Without considering the horizontal variations in the chimney, not surprisingly theoretical predictions by this model can significantly overpredict the experimental measurements as shown by Chen et al. (2003), Jing et al. (2015) and Liu et al. (2015).

Recently, Khanal and Lei (2014a) analyzed the development of the boundary layer inside a solar chimney using a scaling method and suggested that the order of magnitude of the mass flow rate for laminar flows is as follows.

$$\dot{m} \sim \begin{cases} \frac{\lambda}{C_p}\left(\frac{RaPr}{(H/w)^2}\right)^{1/3} & \text{(with a distinct boundary layer)} \\ \frac{\lambda}{C_p}\left(\frac{Ra}{(H/w)^3}\right)^{1/2} & \text{(without a distinct boundary layer)} \end{cases} \quad (3)$$

A distinct thermal boundary layer is present when the boundary layer thickness is smaller than the gap distance. Otherwise, a distinct thermal boundary layer is not available when the boundary layer thickness exceeds the gap distance. The authors showed that the above scaling analysis conforms well with the CFD results.

CFD techniques are applied to address the non-uniform distribution of the airflow in the cavity (Nouanégué and Bilgen, 2009; Zamora and Kaiser, 2009; Andreozzi et al., 2009; Amori and Mohammed, 2012). CFD simulations can provide more detailed information on the airflow subjected to complex boundary conditions (Wang and Pepper, 2009; Wei et al., 2011; Timchenko et al., 2015; Hong et al., 2015) and capture complicated flow patterns, such as reverse flow, which can have adverse effect on the chimney performance (Khanal and Lei, 2012). Recently, Shi and Zhang (2016) used a validated CFD model to generate an empirical model for the prediction of flow rate in a solar chimney. Although CFD simulations can offer details, the modeling itself is a complicated process and often involves time-consuming iterations, and the results are sensitive to the uncertainties in the detailed boundary conditions and require validation. In addition, one should be cautious to extend results from one case to another.

In building energy simulation that involves solar chimney design, a model is often needed to be able to provide a fast and reliable evaluation of the chimney effect. Although potentially accurate, CFD is not a suitable option because of the time-consuming iterations. In this study, we propose a new analytical model for such purpose. The new model addresses both the vertical density stratification and the horizontal density non-uniformity in the solar chimney channel. We validated this model using experimental data from the literature.

2. Modeling of the solar chimney

A typical solar chimney mainly consists of two heated walls, one opening at the bottom, and one opening at the top. In experimental models, the solar chimney is often simulated with only one wall heated by electrical plate, hot oil, or other heating methods. The channel is insulated. In the practical application, one of the walls is transparent to allow sun light to go through and heat the channel. The space from which the solar chimney draws air can be different from one to which the solar chimney discharges air. For example, a solar chimney can be used to draw air from the room and discharge to the outside in an enhanced natural ventila-

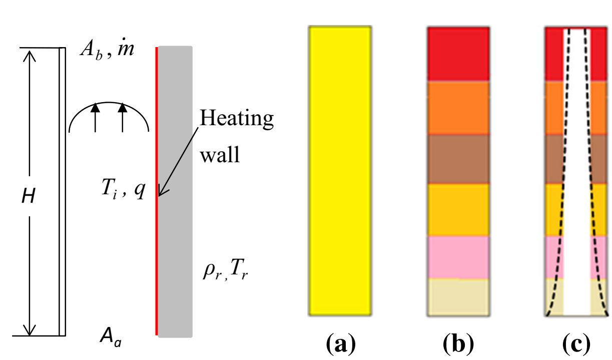

Fig. 1. Configuration of solar chimney and their model representations: (a) single zone model; (b) stratification model; and (c) plume model.