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Influences of ambient air speed and internal heat load on the performance of solar chimney in the tropics

Alex Yong Kwang Tan *, Nyuk Hien Wong

Department of Building, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore

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Abstract

Solar chimney is a combination of solar assisted stack and wind driven ventilation where air in the solar chimney expands under heating from solar irradiance and being relatively lighter, rises out from the chimney outlets, drawing the cooler air into the building through the fenestrations. This pull effect is complemented further by the push effect from the outdoor ambient wind. The study of solar chimney system within the zero energy building in tropical Singapore aims to determine the effects of ambient air speed and internal heat load on the thermal environment of the solar chimney ducts and classroom's interior. Experimental and computational results show that high ambient air speed greater than 2.00 m/s improves the air speed within the solar chimney ducts; both low and high ambient air speeds are found to improve the classroom's interior air speed. However, the significance of ambient air speed drops when solar irradiance is greater than 700 W/m^2. Furthermore, under the tropical weather conditions of high solar irradiance and low ambient air speed, cross ventilation performs better compared to solar chimney; hence, solar chimney is recommended to be employed under zero ambient air speed. Lastly, results show that the influences of internal heat load on the air temperature and speed within solar chimney ducts as well as classroom's interior are limited.

Keywords: Solar chimney; Tropics; Ambient air speed; Internal heat load

1. Introduction

The principle of the solar chimney effect is a combination of solar assisted stack and wind driven ventilation. Air in the solar chimney expands under heating from the sun and being relatively lighter, rises out from the chimney outlets, drawing the cooler air into the building through the fenestrations. This pull effect is complemented by the push effect from the outdoor ambient air.

Although the underlying principle of solar chimney is well understood, the state of the art research concentrates on the design aspect of the solar chimney and its performance under different climate. The purpose of this study aims to examine the performance of solar chimney in the tropics; a hot, cloudy and humid weather conditions.

This issue is interesting because solar chimney ventilation performs optimally not only when the temperature difference between the interior and exterior environments is great, but when the exterior temperature is low. However, being in the tropics, the interior–ambient temperature difference is commonly less than 5 °C, with a high exterior temperature beyond 30 °C.

This paper aims to examine the performance of solar chimney system under the influences of ambient air speed and internal heat load (combined heat gains due to human

* Corresponding author. Tel.: +65 6516 5845; fax: +65 6775 5502.
E-mail address: alextanyk@alumni.nus.edu.sg (A.Y.K. Tan).

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presence). This issue is interesting because researchers gave mixed and limited review on this parameter. Furthermore, most solar chimney research concentrated on enhancing the thermal stack effect and hence the wind assisted effect was mostly ignored.

In addition, internal heat load is commonly researched upon in mechanical ventilation system (Yin et al., 2009) as well as atrium stack ventilation (Liu et al., 2009). As literature on the influence of internal heat load on solar chimney performance is limited, it is worthwhile to examine its significance.

2. Literature review

Solar chimneys originated from wind towers and stack assisted chimneys, and were popularised with the development of the Trombe–Michel wall. Brockett and Albright (1987) developed a theoretical model to predict the natural ventilation rates of a building using both thermal and wind induced pressure flows; in order to maintain a fixed ventilation rate, the total vent area should increase with the increasing outside temperature, decreasing wind speed or decreasing rooftop opening width.

Bansal et al. (1994) derived the theoretical volume flowrate for solar chimney under the assistance of wind tower by varying the solar irradiance and the ambient air speed. Results showed that volume flowrate increased with both solar irradiance and ambient air speed. However, the effect of ambient air speed was more significant at low irradiance.

Ekechukwu and Norton (1997) observed the performance of a circular solar chimney. A solar radiation absorbing surface within the chimney was determined to improve its performance and the absorbing surface temperature was found to increase with height.

Gan and Riffat (1998) examined the performance of solar chimney using two dimensional Fluent simulations. Using double glass glazing, with increasing solar heat gain, the volume flow rate was found to increase at the same time.

Khedari et al. (2000) determined the effects of different opening vents of roof solar collectors on the thermal comfort of a building. It was observed that the airflow rate was independent of ambient air speed as loss of solar-induced ventilation was compensated by the wind-induced ventilation.

Kazansky et al. (2003) carried out smoke visualisation, scaled experiments and Fluent CFD simulations of varying solar chimney' height and found that as the height increased, the temperature within the solar chimney decreased significantly due to a great heat transfer from higher air speed. The experimental and simulated mass flowrate obtained differed by less than 20%.

Heras et al. (2005) carried out analysis on a building of the University of Almeria in Spain. The 5 m high solar chimney showed that the ambient air speed, ambient–indoor temperature difference as well as the thermal gradient along the height of solar chimney had a combined effect on the solar chimney's performance.

Chantawong et al. (2006) developed a computational model of glazed solar chimney wall (GSCW) which was solved using an explicit finite-difference method coupled with Gauss–Seidel iteration. This model was compared with experimental data obtained from a prototype concrete building. The GSCW gave an induced inner air speed within the range of 0.07 m/s to 0.14 m/s with a temperature difference of 1.1 °C within the GSCW.

Tan et al. (2007) carried out two-dimensional steady state simulations together with experimental validation on a rooftop solar chimney. Results showed strong influences and interaction between the inclination angles and solar chimney's depth on the mass flow rate.

Sakonidou et al. (2008) proposed a theoretical model to determine the tilt of a solar chimney that maximised airflow. The results were compared with two dimensional CFD simulations and full-scale solar chimney experiments. In addition, the CFD simulations agreed well with the experimental data conducted in Serres, Greece.

Arce et al. (2009) set up a solar chimney facing south in outdoors Tabernas, Spain, constructed from reinforced concrete painted black with a glass cover. Experiments found that the airflow rate was observed to be caused by a combination of the thermal gradient and ambient air speed.

Tan and Wong (2012) examined the solar chimney's performance in the tropics and reported that the interior air temperature cooled down faster and heated up slower. In addition, the position of the inlet of the solar chimney within the interior was found to influence the interior air speed. Furthermore, a regression model is proposed by Tan and Wong (2013) to determine an optimal tropical solar chimney design.

From literature review, the influence of the ambient air speed is fairly inconclusive. Furthermore, limited research examines the effect of internal heat load on the performance of solar chimney. Lee and Strand (2009) using energy balancing simulation EnergyPlus set an internal heat gains from lights and equipment having value of 5.4 W/m^2 together with two occupants. However, results were not compared with similar conditions without internal heat generation.

It is clear that research on the application of solar chimneys is generating interests worldwide. However, research generally concentrated on temperate countries with weather conditions very different from the tropics.

Tropics are different from the temperate regions in term of the sun's path, the amount of solar irradiance and the speed of ambient air. The maximum solar irradiance in Zurich, Switzerland was 438 W/m^2 in the winter (Gan, 1998) while in Singapore, the maximum solar irradiance easily reach 1000 W/m^2 and beyond, the average ambient air speed in Tabernas, Spain is 5 m/s (Arce et al., 2009) while in Singapore, ambient air speed hardly goes beyond 2 m/s.

3. Methodology

Experiments were conducted within the Zero Energy Building (ZEB), a three-stories building measuring 64.2 m