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Simulation and measurements of wind interference on a solar chimney performance

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ABSTRACT

The solar chimney is a stack-induced ventilation strategy used to improve thermal performance in buildings. Besides operating via a buoyancy-driven airflow, even low velocity winds can affect the chimney functioning in both positive and negative ways. In technical literature, though, few studies have considered the influence of wind speed and direction, as well as discharge coefficients and wind pressure coefficients. This paper investigates the effects of wind interference on a solar chimney performance, through different scenarios of wind speed and direction, over a base case model. Wind tunnel experiments and computer simulations using EnergyPlus were carried out to perform qualitative and quantitative analyses of the airflow, as a function of the combined effect of thermal and wind components. Results showed that the airflow rate and distribution pattern at the outlet openings of the solar chimney are influenced by either the thermal gradients and, mainly, by the outdoor wind velocity and direction. A significant reduction in the volumetric flow rate of the chimney is observed due to wind incidence opposite to the inlet opening, even at low velocities, such as 0.6 m/s.

1. Solar chimneys and wind: introduction

Solar chimneys use energy from solar radiation to heat the air and induce the stack effect, by increasing the pressure and temperature differences between inlet and outlet openings. They are an appropriate strategy for sites with low-velocity or no wind, where the use of thermally induced ventilation can produce better results than ventilation driven by aeromotive forces (Bansal et al., 1994).

In recent years, experimental, numerical and theoretical investigations have contributed to the current research and development of the solar chimney strategy. Mathur et al. (2006), for example, performed experimental and theoretical investigations to analyse the effect of the inclination of the absorber on the airflow rate of a solar chimney. Results of the developed solution showed that optimum absorber inclination varied from 40° to 60°, depending upon the latitude of the location. Nugroho (2009) presented a research focused on optimising the solar chimney geometry to improve stack ventilation for thermal comfort in tropical conditions. Results showed that optimisation of the geometry could improve the indoor air velocity for increased ventilation. Furthermore, Pavlou et al. (2009) also provided information about the optimum sizing of solar chimney parameters, in order to provide enough ventilation to buildings. The authors investigated the construction thickness, the thermal resistance of the walls, the absorptivity of the internal surfaces, the thermal mass of the chimney and the type of glazing.

In technical literature, few studies have considered the influence of wind on the performance of solar chimneys. Most studies have concentrated solely on the air movement due to stack effect. Yet, a major uncertainty in the design of naturally ventilated buildings with stack effect is the interference of the unsteady wind on the airflow, due to the occurrence of reversal flow, which can appear even in the presence of buoyancy (Chiu and Etheridge, 2004). Indeed, when combining thermal buoyancy and wind action, dynamic variables like the wind incidence are as important as thermal variables (Delgado et al., 1996). According to Marques da Silva (2003), the wind interference must be considered even when the design considers the thermal component as the “engine” of the process. In cases where there are openings for natural ventilation at different heights and a wind velocity of 1 m/s, for example, the contribution of the wind corresponds to the same airflow obtained with an 8 K temperature difference between the indoor and outdoor air. For a wind velocity of 5 m/s, the estimated airflow due to the wind is twice as high as the airflow obtained by a temperature difference of 24 K.

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A Systematic Mapping Review was performed to map the frequency of publication on this research topic. Results from Science Direct database showed a total number of 161 publications on the subject 'solar chimney', but only nine publications on the subject 'solar chimney and wind' (after filtering by title, abstract and keywords). Table 1 summarizes the results of the detailed review of these papers.

Bansal et al. (1994) experimentally studied a solar chimney coupled to a wind tower to induce natural ventilation in a multi-story building. The proposed system consisted of the installation of solar chimneys attached to outlet openings, aiming to aid the air exhaust. The outdoor wind was supposed to be captured at the tower inlet and directed downwards to be distributed to the rooms. As expected, the increase in airflow caused by the solar chimney coupled to the wind tower was greater at lower wind velocities. For example, for a wind velocity of 1.0 m/s and 700 W/m^2 of incident solar radiation, the mass flow rate obtained from the wind tower was 0.75 kg/s, whereas the system with a solar chimney was capable of obtaining flow rates up to 1.4 kg/s.

After comparing simulated and experimental results and noting that the airflow due to wind could not be neglected, Afonso and Oliveira (2000) proposed a modification to a system of equations in order to consider this effect. The proposed theoretical model combined equations for heat transfer with equations for natural ventilation. A Test Reference Year (TRY) weather file was used, including information about wind velocity and direction. The wind pressure coefficients were calculated using the CPCALC software. The modification resulted in a closer relation between experimental and calculated data. However, as the wind varies constantly its speed and direction, the authors proposed that a solar chimney design should be developed without considering wind effects, which would, occasionally, underestimate the actual ventilation rates. In fact, if correctly designed, a solar chimney subjected to wind forces may perform better than a solar chimney that acts solely based on temperature difference.

Chungloo and Limmeechokchai (2007) tested the use of a wind shield to reduce the effects of the prevailing winds on the induced ventilation of a solar chimney test cell. The experimental results showed that, without the wind effect, the solar chimney could provide an airflow between 1.13 and 2.26 air changes per hour (ACH), which consisted in 7.5%–15.1% of the airflow compared to the solar chimney subjected to wind effect. The low ventilation rates obtained by using solely buoyancy forces showed that the wind effect should be included in the natural ventilation application.

Arce et al. (2009) demonstrated that even low velocity winds can affect the chimney functioning in both positive and negative ways. Their experimental apparatus, which was constructed in South-Eastern Spain (37°05' North latitude), consisted of a 4.5 m high, 1.0 m wide and 0.15 m thick vertical chimney, with a 0.3 m deep air channel and a concrete wall absorber. To reduce the pressure drop through the chimney channel, the prototype was constructed with inlet and outlet openings of equal areas. The outlet opening was protected against reverse flow, such that the opening could always be positioned in the opposite direction of the incident winds. Results showed that the airflow inside the solar chimney was affected by the pressure difference between inlet and outlet caused by thermal gradients and, primarily, by wind velocity. When wind velocity was at a minimum, an airflow of 50 m^3/h inside the solar chimney was registered. The average airflow measured inside the channel was of 177 m^3/h during the day.

Zamora and Kaiser (2010) also registered a gap in the study of ventilation through solar chimneys exposed to wind. The authors developed a numerical model of the airflow in a vertical solar chimney induced by both wind and buoyancy. The model assumed a uniform heat flow inside the channel and a uniform surface temperature on the absorber, and the airflow varied between laminar, transient and turbulent depending on the magnitude of the buoyancy forces. The analyses were performed using the Fluent code. The authors analysed the numerical results for wind pressure coefficients, convective heat transfer coefficients (Nusselt number), degree of the airflow turbulence (Rayleigh number), and their correlations with the mass flow rate. Results indicated changes in the system's behaviour when a transition from laminar to turbulent flow occurred. For very low Rayleigh numbers, the buoyancy effects were almost insignificant compared to the wind forces, except for very low wind velocities. For high Rayleigh numbers, the wind effects became important at velocities of approximately 1–2 m/s, and between 2 and 3 m/s, the wind effects were prevalent.

According to Alemu et al. (2012), a number of mathematical models to predict the mass flow rate in solar chimneys do not consider the variation of building's static pressure from the atmospheric pressure. The authors therefore developed a mathematical model that could predict reverse flow in the solar chimney, based on a critical pressure zone about which the airflow direction changed.

Al-Kayiem et al. (2014) investigated the influence of the chimney height, area and wind speed effect on a solar chimney performance. The inclined rooftop solar chimney model comprised two sides, one on each side of the roof. The authors concluded that when the speed increased from 1.5 m/s to 6 m/s, the effect on the system's performance became significant for a solar intensity higher than 400 W/m^2. At solar intensity of 900 W/m^2, for example, increasing the wind speed from 1.5 m/s to 6 m/s caused reduction in the system performance of about 25%.

Tan and Wong (2014) determined the effects of ambient air speed and internal heat loads on a solar chimney coupled to a net zero energy consumption building located in Singapore. Results showed that both low and high winds improved the indoor air speed. However, the wind impact dropped when solar irradiance was greater than 700 W/m^2.

Table 1
Publications on the subject 'solar chimney and wind' – Science Direct database.

Authors (date)	Object of analysis	Method	Discharge coefficient (Cd)	Wind pressure coefficients (Cp)
Bansal et al. (1994)	Solar chimney coupled with a wind tower	Mathematical model	Based on an Indian Standard	Derived from a mathematical model
Afonso and Oliveira (2000)	Vertical solar chimney	Experimental test cell and mathematical model	Not mentioned	Derived from CPCALC software
Chungloo and Limmeechokchai (2007)	Rooftop solar chimney	Experimental test cell	Derived from measured values	Not mentioned
Arce et al. (2009)	Vertical solar chimney	Experimental test cell	Derived from measured values	Not mentioned
Zamora and Kaiser (2010)	Vertical solar chimney	Mathematical model	Not mentioned	Derived from a mathematical model
Alemu et al. (2012)	Roof and wall mounted vertical and inclined solar chimneys	Mathematical model	Not mentioned	Based on AIVC's wind pressure coefficients guide for low rise buildings
Al-Kayiem et al. (2014)	Rooftop solar chimney	Experimental test cell and mathematical model	Based on Arce et al. (2009)	Not mentioned
Tan and Wong (2014)	Vertical solar chimney	Experimental study in real building and CFD simulation	Not mentioned	Based on PRESTO! (PREssure STaggering Option) scheme
Hosien and Selim (2017)	Vertical solar chimney	Mathematical model	Based on ASHRAE Standard	Based on ASHRAE Standard