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Prediction of airflow rate through a ventilated wall module

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ABSTRACT

When outdoor air becomes polluted by airborne particles and noise, it is necessary to use a new type of outdoor air intake device that is able to clean the extracted air and insulate the noise. One possibility is to adopt a ventilated wall module that contains a porous filtration unit. To use solar irradiation, a solar channel is attached to the ventilated wall module to heat the air and to propel the air movement. The driving force of air ventilation can be the stack pressure, the wind pressure, a combination of the two, or external fans. This investigation developed a lumped correlation analysis model to predict the volumetric flow rates versus the driving pressure. The correlation model was established based on energy conservation and pressure balance laws. In addition, the computational fluid dynamics (CFD) modeling was also implemented to predict the ventilated wall performance. To validate both types of models, a ventilated wall prototype model was constructed in the lab. Both pressures and induced volumetric flow rates were measured by a high-precision micro-manometer. It is found that the correlation analysis model obtained results in reasonably good agreement with the experimental data, which suffices for engineering design.

1. Introduction

For buildings using natural ventilation, outdoor spaces and indoor spaces are directly connected via ventilation openings. In case the outdoor air is polluted by airborne hazards or noise, the outdoor pollution may easily penetrate into the interior space through the ventilation openings. This can occur in dense cities, where the outdoor environment is not always ideal. New types of outdoor air intake devices that are able to filter the outdoor air and insulate the noise are needed. Ventilated wall modules provide a promising way to fulfill this task. Fig. 1(a) and (b) shows our design of a ventilated wall, in which a zigzag flow channel is connected in series with a porous filtration unit. A board for solar radiation absorption is mounted within the outer channel to heat the air streams in winter. However, in summer, the outer channel can behave as a solar chimney by switching baffles to induce air permeation through the porous filtration unit so that the air introduced into the room space is not heated. The ventilated wall module is different from the dynamic insulation that is essentially a kind of porous wall [1], in which the air permeation through the porous wall is minimized to obtain good thermal insulation. This is because the weak air motion in dynamic insulation is dedicated for recovering the conduction heat loss instead for providing the outdoor air like the ventilated wall module.

The ventilated wall module can be installed below a well-sealed glass window for intake of the outdoor air, as shown in Fig. 1(c), and then the traditional window is used only for its optical purpose instead for ventilation. Note that the ventilated wall module is purely a device to draw in the outdoor air rather than an air conditioner. In extreme weather conditions, a radiator or an air conditioner may still be required to condition the room air temperature to the appropriate status. The driving force for outdoor air permeation into the room can be the stack pressure (due to the solar radiation), the wind pressure, their combination, or external exhaust fans. When there is neither solar radiation nor wind in the nighttime, an external fan must be operated to draw in the outdoor air.

To optimize the ventilated wall design, the outdoor air drawing rate should be determined. The outdoor air extraction rate depends on the outdoor wind, solar irradiation, geometric parameters of the wall, and the porous filter characteristics, etc. If the room exhaust fan is not in operation, the induced airflow rate is subject to both the stack pressure and the wind pressure. Once the ventilated wall design is fixed, the flow resistance of the wall is set. The relationship between the driving pressure and the flow resistance can be solved to predict the airflow rate. This investigation attempts to predict the induced airflow rate through the wall by both lumped correlation analysis and computational fluid dynamics (CFD) modeling.

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Nomenclature

A_i	channel cross-sectional area (m^2)
A_j	inlet, outlet or duct fitting area (m^2)
A_{pm}	porous media cross-sectional area (m^2)
B	coefficient (m^2)
C_p	constant-pressure specific heat (J/kg °C)
C_{sp}	surface-averaged pressure coefficient
C_2	inertial resistance factor
C_{pm}	porous media resistance coefficient
D_i	hydraulic diameter of the channel (m)
D_{pm}	equivalent diameter of the quartz sands in the porous media filter (m)
f_i	friction factor
g	gravitational acceleration (m/s^2)
H	outer channel height (m)
K_j	loss coefficient
L_i	length along the flow path in a section (m)
p_w	wind pressure (Pa)
q''	heat generation flux (W/m^2)
S_i	momentum source term
T_{ave}	average air temperature inside the outer channel (°C)
T_∞	ambient temperature (°C)
U	outdoor mean wind speed (m/s)
$\dot{V}$	volumetric flow rate through the ventilated wall (m^3/s)
$\|v\|$	magnitude of the velocity (m/s)
v_i	velocity component in the ith direction (m/s)
w	width (m)
x	length in the X-coordinate (m)
y	length in the Y-coordinate (m)
z	length in the Z-coordinate (m)

Greek symbols

α	permeability
β	thermo expansion coefficient (1/K)
μ	dynamic viscosity (Pa·s)
ρ	air density (kg/m^3)
φ	porosity
ψ	resistance along the whole flow path (kg/m^7)
ΔH	piling height of the sand particles (m)
ΔP_s	stack pressure difference (Pa)
ΔP_t	total pressure difference (Pa)
ΔP_w	wind pressure difference (Pa)

An experimental measurement was also carried out to validate both prediction methods.

2. Overview of investigation of natural ventilation rate

To the best of our knowledge, no research has been performed on investigating the airflow rates through a ventilated wall module as shown in Fig. 1, which combines a solar channel and a porous filtration unit. However, numerous studies have been conducted for solar chimneys and ventilated facades. In the following, the review will be concentrated to measurement and prediction of airflow rates through solar chimneys and ventilated facades. Nevertheless, some basic principles between the ventilated wall module and the solar chimneys and ventilated facades are similar.

2.1. Measurement studies

Airflow rates driven by stack pressure have been extensively measured for solar chimneys. Chen et al. [2] measured the velocities across a chimney gap in a lab and found that air speeds are essentially uniform across the chimney width for the gap-to-height ratio ranging from 1:15 to 2:5. However, air speeds and temperatures can be highly non-uniform for vertical chimneys with large internal gaps. Burek and Habeb [3] measured the mass flow rates through a heated channel that resembles either a solar chimney or a Trombe wall. They concluded that the induced mass flow rate varies with the heat flux with an exponent of 0.572 and varies with the channel gap size with an exponent of 0.712. Measurement of air speeds were also carried out in a channel behind the photovoltaic panels with one side heated and the other side insulated [4,5]. The air speeds were proportional to the heat flux with an exponent of 0.353 [4], or an exponent of 1/3 for turbulent flows and 1/2 for laminar flows [5]. Khedari et al. [6] implemented field measurement of the volumetric flow rates through a solar chimney for an air-conditioned house in a tropical region.

In addition to the stack pressure, the mass flow rates by both the stack and the wind pressure were also measured for a solar chimney under real meteorological conditions [7] and for an opaque ventilated facade [8]. Lou et al. [9] measured the wind-driven airflow rates via double-skin facades of a tall building using scale models in a wind tunnel and obtained very complicated pressure profiles on the facades that may be useful for airflow rate prediction.

2.2. Analytical correlations

Compared to experimental studies, analytical/numerical investigations have more flexibility. The analytical method treats the ventilated wall as a single point device and then solves the pressure-resistance relation for the airflow rate. The analytical model provides the simplest and most efficient formula to predict the induced airflow rates via ventilated devices. Chen et al. [2] proposed an analytical formula to estimate the volumetric flow rate through a solar chimney by implementing a balance between the stack pressure and the pressure loss. Sandberg and Moshfegh [5] carried out similar lumped parameter analysis and summarized correlations for both turbulent and laminar flows in a heated channel behind the solar cells. Rodrigues et al. [10] proposed expressions of volumetric flow rates for a solar channel based on the integral equations of motion and the Bernoulli theorem. Bansal et al. [11] and Andersen [12] proposed a widely used formula for the mass flow rate through a solar chimney by implementing a balance of the stack pressure and the kinetic pressure. Later, AboulNaga and Abdrabboh [13] supplemented the analytical expression of temperature distribution within the chimney to improve the mass flow rate prediction.

2.3. Zonal modeling

To account for temperature and pressure difference along the flow path, numerical modeling such as zonal or CFD simulation may be applied. The zonal modeling divides the device into several zones and solves for the mass, pressure and energy balance across each zone. The zonal model provides an efficient numerical solution that does not sacrifice accuracy too much. Jiru and Haghighat [14] applied the zonal model to compute the airflow rates through a double-skin facade that contains blinds. The mass flow rate is assumed to vary with the zonal pressure difference with an exponent of 0.5. López et al. [8] established a five-zone model for an open ventilated facade and calculated the mass flow rates between different zones as a function of the square root of the zonal pressure difference. The predicted temporal rates were in good agreement