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Wind-driven cross ventilation with internal obstacles

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ABSTRACT

Most ventilation models do not consider the influences of furniture and obstacles on building ventilation. This study developed a resistance model to calculate the ventilation rate of wind-driven cross ventilation in a low-rise building with vertical plates in the building. The flow resistances generated by the plates of various sizes were systemically investigated using a Large Eddy Simulation model and wind tunnel experiments. The numerical and experimental results consistently demonstrated that the resistance factor is a function of the internal blockage ratio (ratio of the plate area to the internal cross-section area) and location, but is independent of the external wind speed, building size and opening configuration. It was also found that when the wall porosity is less 3%, the resistances caused by the external openings will dominate the ventilation process and the influence of the internal obstacles on the ventilation rate can be neglected. But when the internal resistance is larger than the external resistances, the diminish effect of the obstacles on the ventilation rate should be taken into account.

1. Introduction

Wind-driven natural ventilation is widely used to maintain comfortable indoor environments and to save energy consumption for residential buildings in tropical areas [1,2]. Therefore, simple and accurate prediction methods of building ventilation are essential for the design and utilization of wind-driven ventilation. The most widely used method to calculate the ventilation rate, Q, through a building opening, is the orifice equation [3–5]:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where A is the cross-sectional area of the opening, $\Delta P = \left|P_e - P_i\right|$ is the difference of external and internal pressures, ρ is the density of the air, and C_d is the discharge coefficient. Typical discharge coefficients given in the literature are in the range of 0.60–0.65 for sharp-edged openings [3–5]. Eq. (1) is derived from Bernoulli's assumption of inviscid, incompressible flow, and has been widely used in multi-zone models [6–8]. However, several studies [9,10] have pointed out that the orifice equation could not be used to predict the flow rate of wind-driven cross ventilation and the discharge coefficient is difficult to determine and cannot be regarded as a constant. Chu et al. [11], based on their wind tunnel experiments, found that the discharge coefficient of an external opening is dependent on the opening Reynolds number.

For wind-driven cross ventilation, Ohba et al. [12] used wind tunnel experiments and split-film anemometer to investigate the wind-driven cross ventilation and found that the penetrating flow entered the inlet opening and deflected downward toward the floor. Karava et al. [13] utilized the wind tunnel and particle image velocimetry (PIV) to measure the velocity field inside a single-zone building model for several different opening configurations. They found that the orifice equation predict the ventilation rates reasonably well, for two of the three opening configurations examined, when the wall porosities were less than 10% and the momentum of the approaching flow did not contribute substantially to the ventilation rate.

Additionally, several studies applied the energy balance concept to investigate the wind-driven cross ventilation. Kobayashi et al. [14] employed standard k-ε model and the Reynolds stress model to study the transported power and power loss of cross ventilation in pitched roof and rectangular buildings. They discovered that the opening porosity did not significantly influence the power loss of the stream tube through the building. Chu et al. [15] used wind tunnel experiments to investigate the wind-driven cross-ventilation of partitioned buildings. They found that, due to the extra resistance caused by the partition, the ventilation rate of a partitioned building is always smaller than that of a single-zone building.

However, the above studies did not consider the obstruction caused by large furniture, short partition wall or other obstacles in the path of the air flow. These obstacles inside the building may change the air flow path and reduce the ventilation rate. In other words, it is possible to over-estimate the ventilation rate by using

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Notation

A_1, A_2 cross-section area of external opening (m^2)
A_2/A_1 opening ratio (dimensionless)
A_i cross-sectional area of building interior (m^2)
A_F area of the windward facade (m^2)
A_p area of the plate (m^2)
C_d discharge coefficient of opening (dimensionless)
$C_p = (P - P_o)/0.5\rho U_H{}^2$ external pressure coefficient (dimensionless)
b width of plate (m)
h height of plate (m)
H height of building (m)
L length of building (m)
P_o reference pressure (Pa)
Q ventilation rate (m^3/s)
Q^* dimensionless ventilation rate
$r_p = A_p/A_i$ internal blockage ratio (dimensionless)
$r_1, r_2 = A/A_F$ external wall porosity (dimensionless)
U_o free stream wind speed (m/s)
U_H wind speed at the building height (m/s)
W width of building exterior (m)
X distance from the windward wall to the plate (m)
z elevation (m)
ρ air density (kg/m^3)
g gravitational acceleration (m/s^2)
α the exponent of the velocity profile
δ thickness of boundary layer (m)
θ wind direction (degree)
ζ_i internal resistance factor (m^{-4})
ζ_1, ζ_2 external resistance factor (m^{-4})

Subscripts
1 windward side
2 leeward side
3 internal

Eq. (1) for wind-driven cross ventilation. Aynsley [16] proposed a resistance approach to calculate the ventilation rate through building openings, but he did not provide a scheme to calculate the resistance of the internal obstacles in the buildings.

Chu and Wang [17] used the energy equation and resistance concept to derive the ventilation rates of partitioned buildings. Their resistance model could be extended to building with internal obstacles. Assuming the windward and leeward façades of the building each has one opening (see Fig. 1). The energy equation is:

$$\frac{P_1}{\rho g} + z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\rho g} + z_2 + \frac{V_2^2}{2g} + k_i \frac{V_i^2}{2g} \qquad (2)$$

where P is the pressure, z is the elevation; g is the gravitational acceleration, V is the average velocity in the room; subscripts 1 and 2 represent the windward and leeward façades, respectively. The last term on the right hand side is the energy loss due to the obstacle, with V_i as the velocity through the obstacle, and k_i is the loss factor. The loss factor k_i is a dimensionless coefficient, depending on the configuration of the internal obstacles. In single-floor buildings, the difference in elevation $\Delta z = z_1 - z_2$ is negligible. Assuming the mean velocities in front of and behind the obstacle are close to each other, the velocity head $V^2/2g$ on both sides of Eq. (2) can be neglected.

The dimensionless ventilation rate Q^* is defined as:

$$Q^* = \frac{Q}{U_H A_1} \qquad (3)$$

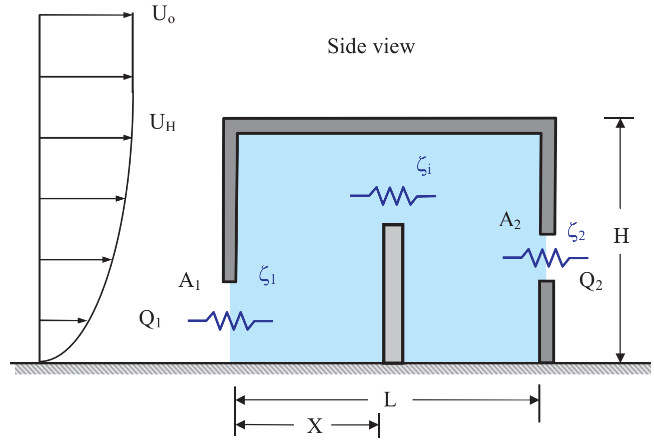

Fig. 1. Schematic diagram of resistances in a building with internal obstacles.

where A_1 is the opening area of the windward opening, and U_H is the external wind velocity at the building height. Using the continuity equation, $Q_1 = Q_2$, and the loss factor of the external opening $k = C_d^{-2}$ [17], one can get the dimensionless ventilation rate Q^* through the windward opening:

$$Q_1^* = \frac{1}{A_1}\left[\frac{C_{p1} - C_{p2}}{\zeta_1 + \zeta_i + \zeta_2}\right]^{1/2} \qquad (4)$$

where C_p is the pressure coefficient on the external wall, ζ_1 and ζ_2 are the resistance factors of the external openings, ζ_i is the internal resistance factor. The resistance factors of external openings can be calculated as follows:

$$\zeta_2 = \frac{1}{C_d^2 A_2^2} \qquad (5)$$

where C_d is the discharge coefficient of external opening, A_1 and A_2 is the area of the windward and leeward opening, respectively. The unit of the resistance factor is [m^{-4}]. Eq. (4) is consistent in dimension and indicates that the pressure difference between the windward and leeward openings is the driving force to overcome the resistances of cross ventilation. The larger the resistance factors ζ are, the smaller the ventilation rate Q will be. Eq. (4) also can be used for buildings without internal obstacles ($\zeta_i = 0$). The extra resistances caused by the partition wall, furniture or other internal obstacles can be expressed in term of internal resistance factor ζ_i. This resistance model is similar to the model proposed by Aynsley [16], but his definition and unit of the resistance is different from Eq. (5), and he did not validate his model with experimental data or numerical simulation. Therefore, validation of the resistance approach for the obstacle effects on the cross ventilation is still needed.

In this study, a Computational Fluid Dynamics (CFD) model and wind tunnel experiments were used to investigate the influences of internal resistance on wind-driven cross-ventilation. The simulation and experimental results were used to develop a predictive model for the resistance factor of internal obstacles. This model can be used to evaluate the influences of large obstacles on wind-driven cross ventilation.

2. Numerical model

In recent years, turbulence models have been successfully applied to building ventilation simulations [18–20]. This study used a three-dimensional Large Eddy Simulation (LES) model to simulate the cross ventilation of a low-rise building with internal obstacles.