An Integrated Model for Wind-Driven Ventilation of Buildings

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SUMMARY:
Natural ventilation is an effective way to reduce energy consumption in buildings compared to mechanical ventilation. Nonetheless, predicting natural ventilation requires considering various parameters, such as building design, external wind speed and direction, window types, and nearby buildings. In the early stage of building design, a simple and comprehensive prediction model is needed to assess the feasibility of natural ventilation under different design conditions. This study integrates a physical model for cross ventilation and empirical formulas for single-sided ventilation to predict wind-driven ventilation of buildings. The prediction model uses reduction factors to account for the diminishing effects of wind direction, window type, nearby buildings, building length, and balcony walls. The predicted ventilation rates are validated by the results of wind tunnel experiments, a CFD model, and an airflow network model. The integrated model is then utilized to realistically assess the natural ventilation potential of a residential building throughout a year. The simulation results reveal that two-sided cross-ventilation can achieve ventilation rates approximately 20 times larger than single-sided ventilation with the same external wind speed and opening area. In other words, ignoring wind direction variation can lead to inaccurate estimates of wind-driven ventilation.

Keywords: Natural ventilation, Wind-driven ventilation, Single-sided ventilation, Reduction factor, EnergyPlus

1. INTRODUCTION

Prediction models for natural ventilation in buildings can be classified into two types: Computational Fluid Dynamics (CFD) models and network multi-zone models. CFD models are effective at predicting building ventilation, provided that the computational domain, mesh size, turbulent model, and numerical scheme are properly handled. Nonetheless, previous studies have mostly focused on using CFD models to simulate cross-ventilation with a windward opening and a leeward opening, and wind direction is perpendicular to the windward façade. This type of cross-ventilation is relatively simple in terms of flow geometry and achieves high ventilation rates, making it easy to obtain good simulation results from the CFD models (Chen, 2009).
On the other hand, network multi-zone models, such as COMIS, CONTAM, and EnergyPlus, are also widely used to predict natural ventilation rates in buildings. These models divide the building interior into numerous zones and assume that the internal pressure and temperature are uniform in each zone. Ventilation rates from one zone to another are computed using the orifice equation or empirical formulas (Etheridge, 2011). For buildings with many zones, the internal pressure of each zone and the ventilation rates can be obtained by solving simultaneous equations of mass conservation. However, these models are not suitable for predicting single-sided ventilation or ventilation with minimal pressure differences between zones (Chu et al., 2015).

2. VENTILATION MODEL

This study integrated a physical model for cross ventilation and empirical formulas for single-sided wind-driven ventilation. The total volumetric flow rate for cross-ventilation into the building when the wind direction is normal to the windward opening ($\beta = 0^o$):

$$\sum Q = A^* U_o \sqrt{C_{pw} - C_{pL}} \quad (1)$$

where U_o is the external wind speed at the opening height; $C_p = (P - P_o)/0.5\rho U_o^2$ is the pressure coefficient; subscripts w and L represent the windward and leeward side, respectively; and A^* is the effective opening area of multi-opening buildings (Chu and Lan, 2019):

$$A^* = \frac{(\sum C_{dwi} A_{wi})(\sum C_{dLj} A_{Lj})}{[(\sum C_{dwi} A_{wi})^2 + (\sum C_{dLj} A_{Lj})^2]^{0.5}} \quad (2)$$

where C_d is the discharge coefficient; A is the opening area; and subscripts i and j are the numbers of openings on the windward and leeward sides, respectively. Chu et al. (2011) used a tracer gas decay method to measure the ventilation rates of single- and two-sided ventilation and found that the cross-ventilation rates under different incidence angles can be described by a cosine law:

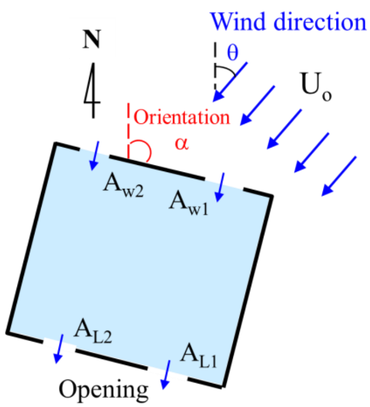
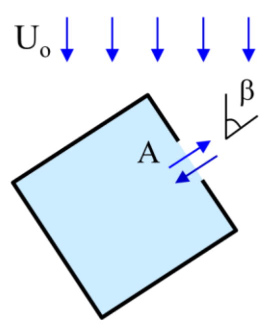
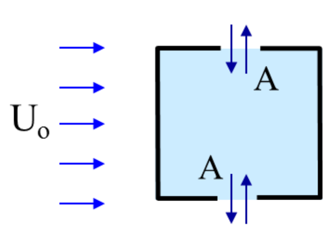
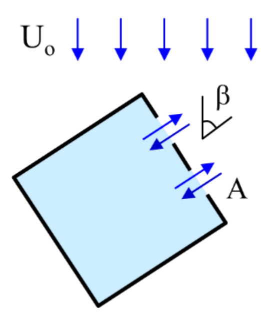
(a) Cross Ventilation	(b) Single-opening Ventilation
	
(c) Shear Ventilation	**(d) Two openings on the same wall**
	

Table 1. Top view of building orientation and wind direction. (a) Cross ventilation; (b) Single-opening ventilation; (c) Shear ventilation; (d) Two openings on the same wall.

$$Q(\beta) = \sum Q_o \cos(\beta) \quad (3)$$

where the relative incidence angle β = α - θ, and θ is the wind direction, α is the building orientation, both angles are relative to the north; and Q_o is the ventilation rate when β = 0°. Chu et al. (2011) also found that the shear flows near the building walls could induce pulsating air exchange across the openings, even the pressure difference between openings is close to zero when the wind direction is parallel to the openings (β = 90°). The exchange rate of single-opening can be predicted by the empirical formula:

$$Q_o = 0.018A \cdot U_o \quad (4)$$

When there are two openings on the same side of the building and no opening on the other side (see Table 1), the ventilation rate is :

$$Q_o = 0.077A \cdot U_o \quad (5)$$

where the opening areas *A* of two lateral openings are the same. The ventilation rate will be mitigated when there are internal obstacles, balcony walls, and adjacent buildings. The ventilation rate under the above diminishing effects can be computed as:

$$Q = K_r Q_o \quad (6)$$

where K_r is the reduction factor of different diminishing effects. For example, the reduction factors for openings with screen, louver, and casement window are K_r = 0.92, 0.77, and 0.31, respectively (Chu et al., 2009).

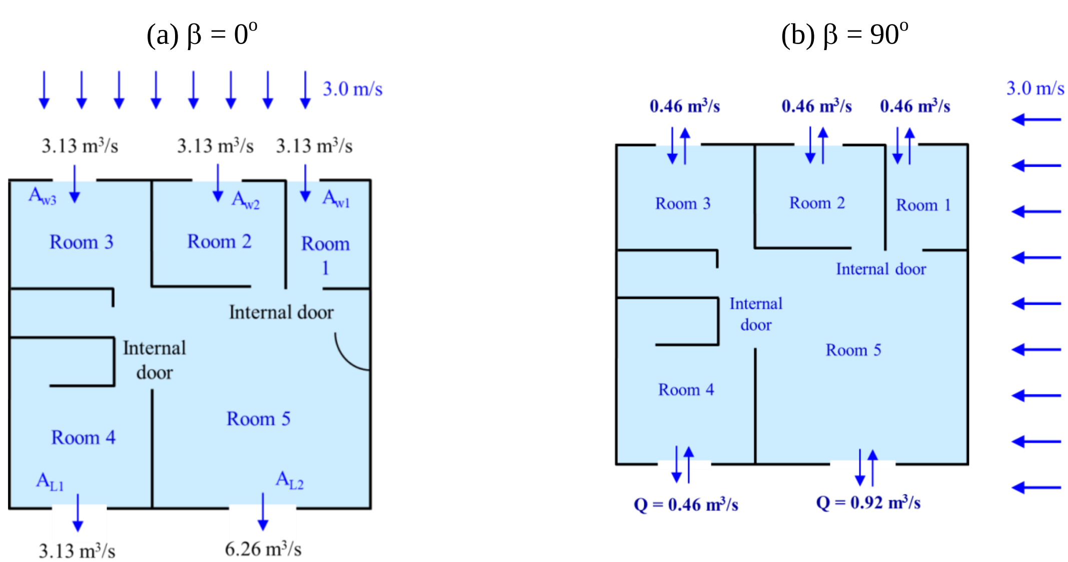


Figure 1. Predicted ventilation rates of the partitioned building. (a) β = 0°; (b) β = 90° (two-sided shear ventilation).

This study applies the integrated model to inspect the wind-driven ventilation rates of a building under two different wind directions. Figure 1 shows the predicted ventilation rates of the incidence angle $\beta = 0^o$ are much larger than that of $\beta = 90^o$ for the same building. The hourly ventilation rates predicted by the present model and the airflow network model of the EnergyPlus for one whole year are compared in Figure 2. As can be seen, the ventilation rates predicted by the EnergyPlus model are smaller than that of the present model due to the EnergyPlus model produces $Q = 0$ when $\beta = 0$ and single-sided ventilation. Besides, the EnergyPlus cannot be used for buildings with multiple openings of different sizes.

3. CONCLUSIONS

Natural ventilation is highly dependent on the wind direction, building design, and the shelter effect of surrounding buildings. This study integrated a cross-flow ventilation model and the empirical formulas for single-sided ventilation, and used reduction factors to account for the effects of window type, and nearby buildings on the ventilation rate. The model predictions were verified by the results of wind tunnel experiments and a CFD model. In addition, the reduction factor approach proposed in this study can be extended to account for the influences of the window curtain, indoor furniture, and surrounding buildings on the wind-driven ventilation rate. CFD models and/or wind tunnel experiments can determine the values of the reduction factors of different effects.

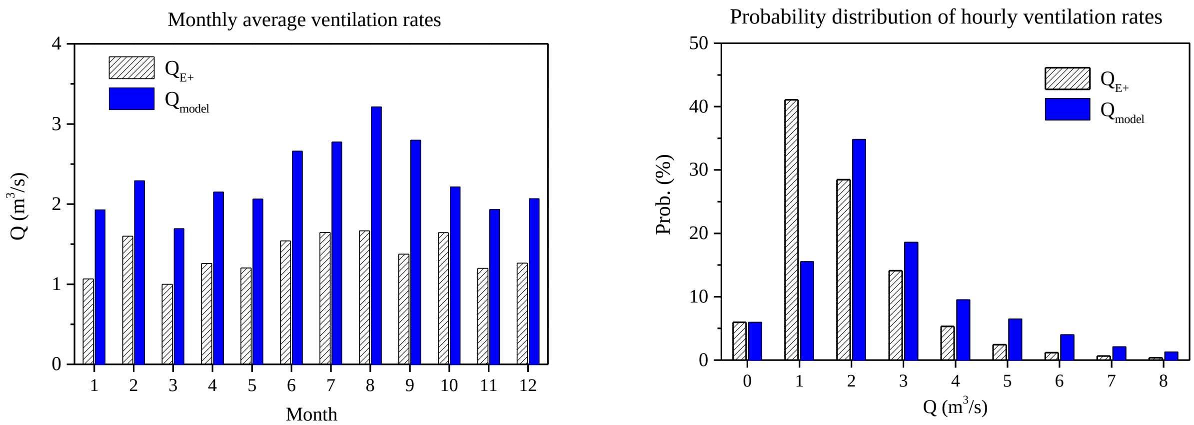


Figure 2. Comparison of predicted ventilation rates by the integrated model and EnergyPlus model. (a) Monthly average ventilation; (b) Probability distribution of hourly ventilation rates.

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