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Modeling of the impact of different window types on single-sided natural ventilation

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Abstract

Natural ventilation can reduce the building energy consumption for cooling and improve indoor air quality. Thus it has gained popularity in recent years. Natural ventilation can be classified as single-sided ventilation and cross ventilation. Cross ventilation can provide higher ventilation rate, however, it can only be used in thin buildings and no large obstacles in the air path. Single-sided ventilation has little restriction and can be easily implemented in buildings. The ventilation rate of single-sided ventilation is hard to predict due to the strong turbulence effect and bi-directional flow occurred at the openings. Our previous study has quantified the effect of mean flow, pulsating flow and eddy penetration on single-sided ventilation rate for simple openings. However, other types of windows such as awning, hopper and casement windows are more commonly used in buildings. To find the impact of different types of windows on single-sided ventilation, this study used Computational Fluid Dynamics (CFD) Large Eddy Simulation (LES) to simulate three different types of windows (awning, hopper and casement) with different opening angles under various wind conditions. The study found the impact of different types of windows on the ventilation rate varied greatly with wind directions, which was due to change of flow pattern introduced by the windows and turbulent effect. This investigation has further developed empirical models for predicting ventilation rate for these types of windows. The models are based on the orifice model and our previous study for simple openings. The model predictions showed good agreement with the CFD simulations.

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Keywords: Natural ventilation; CFD; single-sided ventilation; semi-empirical model

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Nomenclature

A	Area
C_d	Discharge coefficient
C_p	Pressure Coefficient
h	Opening height
P	Pressure
Q	Ventilation rate
U	Wind speed
w	Opening width
z	Z position (Vertical direction)
z_0	Z position of the neutral plane
α	Window opening angle
θ_w	Wind incident angle
Subscript	
ref	Reference (weather station height above ground at 10 m)

1. Introduction

Building uses approximately 40% of the total prime energy in the U.S. [1]. Due to the high energy use, designers are seeking alternative measure to improve the energy efficiency of buildings. Natural ventilation has drawn great attention in the U.S. because it uses no energy while maintains good thermal comfort and indoor air quality [2,3]. However, one of major reasons that prohibits wide application of natural ventilation is the lack of accurate and simple design tools, especially for single-sided ventilation [4]. Furthermore, most of the existing empirical models only apply to simple openings [5,6]. For the typical window types, such as hopper, awning and casement windows, the existing semi-empirical models showed great discrepancy [7]. To properly predict the ventilation rate for those window types, the model should consider both the mean, fluctuating flow and eddy penetration effect, which are the special characteristic of single-sided ventilation [4,8]. Moreover, the model should account for the effect of the flow obstruction created by hopper, awning and casement windows on the ventilation rate. Some researchers modified the discharge coefficients to account for different window types [9,10]. However, this approach considered the impact was constant for all wind directions. A recent study by Gao and Lee [11] revealed that the impact was not constant for all wind incident angles. To properly model the effect of different window types, the model should consider the flow interaction between the window and the incoming wind. To date, our literature indicated that no research has developed simple models for predicting single-sided, wind-driven ventilation rate for various window types.

Therefore, this study would develop new semi-empirical correlations for single-sided, wind driven ventilation rate for hopper, awning and casement windows. Computational Fluid Dynamics (CFD) using Large Eddy Simulation (LES) would be used to generate database to develop the semi-empirical models.

2. Methodology

2.1. Semi-empirical correlations for ventilation rate prediction

Wang and Chen [4] have developed a model for single-sided, wind-driven ventilation with simple opening. Their model accounted for the mean, pulsating flow and eddy penetration effect and showed good agreement with experimental data. Therefore, this study would base the proposed models for different window types on their work. For a simple opening, the ventilation rate can be calculated as [4]:

$$Q = \frac{C_{d,rec} w \sqrt{C_p} \int_{z_0}^{h+h_0} \sqrt{z^{2/7} - z_0^{2/7}} dz}{z_{ref}^{\ 1/7}} U \tag{1}$$

where h_0 is the elevation of the bottom of the opening to the ground. The detailed procedure for calculating neutral plane level can be found in in [4]. The discharge coefficient for rectangular orifice $C_{d,rec}$ is 0.62 [12].

Hopper window

For a hopper window, we could consider it as the half of a converging nozzle as shown in Fig. 1. Therefore, we could use the discharge coefficient of converging nozzle $C_{d,\,converging}$, which is 0.92 [12]. The ventilation rate for hopper windows can be calculated as shown in Eq. (2). The first square root term in Eq. **Errore. L'origine riferimento non è stata trovata.** accounts for the effect of "half" of the converging nozzle and the impact of opening angle. The minimum function ensure the coefficient does not exceed "1" when the opening angle is large enough, at which the opening can be considered as a simple opening

$$Q_{hopper} = \frac{\min\left(\frac{C_{d,converging}}{C_{d,rec}}\sqrt{\frac{\sin\alpha}{2}},1\right) C_{d,rec} w \sqrt{|C_p|} \int_{z_0}^{h+h_0} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{1/7}} U_{ref} \quad (2)$$

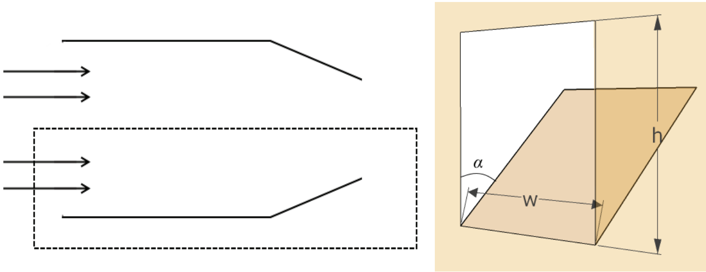

Fig. 1 Schematic of a hopper window

Awning window

For awning windows, the flow can enter the room via two paths as shown in the green areas A_1 and A_2 in

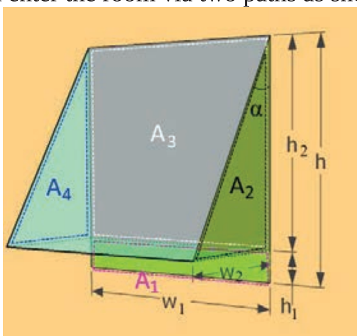

Fig. 2. The ventilation rate due to area A_1 can be calculated as

$$Q_1 = C_{d,rec} w_1 \sqrt{C_p} \frac{\int_{z_{0,1}}^{h_1+h_0} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{1/7}} U_{ref} \quad (3)$$

where $h_1 = h(1-\cos\alpha)$.

For the ventilation rate via A_2, it can be calculated as Eq. (4).

$$Q_2 = \frac{(1-0.5|\cos\theta_w|)}{2} \frac{w_1}{w_1 + \frac{w_2}{2}} C_{d,rec} w_2 \sqrt{C_p} \frac{\int_{z_{0,2}}^{h_2+h_0} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{1/7}} U_{ref} \quad (4)$$

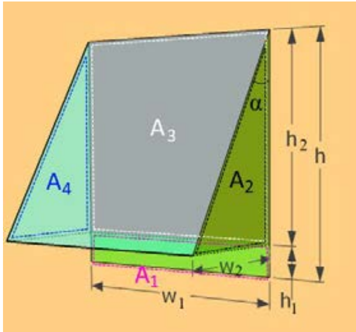

Fig. 2 Schematic of awning window

The “2” in the denominator in the first term accounts for the triangular area. The nominator represents that the ventilation rate through area A_2 is the largest when the wind is normal to A_2 (parallel to the opening). This term is not zero when the wind is parallel to A_2 because there is still eddy penetration effect as quantified by Wang and Chen [4]. The second term represents that only part of the outdoor air through A_2 would enter the room and the rest would leave via Area A_4. We assumed the ventilation rate that could penetrate into the room is proportionate to the area ratio between A_3 and A_3+A_4, which is $w_1/(w_1+w_2/2)$. The total ventilation rate through the awning window is the sum of Eqs. (3) and (4).

Casement window

In this study, we only consider opening angle up to 90° for casement window since it is typically the largest opening angle. Similarly, for casement windows, the ventilation rate could also be approximated as two parts, areas A_1 and A_2, as shown in Fig. 3. The ventilation rate through opening area A_1 is

$$Q_1 = C_{d,rec} w_1 U \sqrt{C_p} \frac{\int_{z_0}^{h+h_0} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{\ 1/7}} \tag{5}$$

where $w_1 = \min\left[1, (1-\cos\alpha)\right] \mathrm{w}$.

The ventilation rate through area A_2 is

$$Q_2 = c\left|\sin\theta_w\right| \cos\frac{\alpha}{2} C_{d,rec} w_2 U \sqrt{C_p} \frac{\int_{z_0}^{h+h_0} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{\ 1/7}} \tag{6}$$

where w_2=$w$sinα and c=1 when 0°≤θ_w≤90°, and 0.5 otherwise because the wind can only “see” opening A_2 when 0≤θ_w≤90°. At other angles, we expected the ventilation rate would be lower because the opening is in weak region and the wind cannot “see” the opening directly. The cosine function represents that part of the outdoor air entering A_2 would be ejected through A_4. The total ventilation rate is the sum of Eqs. (5) and (6).

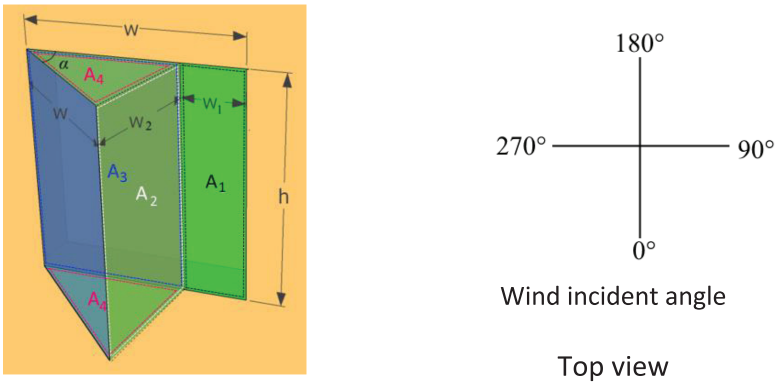

Fig. 3 Schematic of casement window

2.2. CFD Simulations

The CFD LES model was used to generate a database for developing and comparing against the proposed models. The building and opening dimensions are shown in Fig. 4. Table 1 lists all the 52 cases simulated for the database. Since the building is symmetric, we only simulated the wind incident angle from 0-180°. For the casement window , however, since the opening is not symmetric, we simulated the wind angles from 0-360°. The atmosphere boundary condition and model setup were the same as that used by Wang and Chen [4]. This study used structured mesh with finer resolution at near-wall region and the opening. The total number of nodes is 1.4 million.

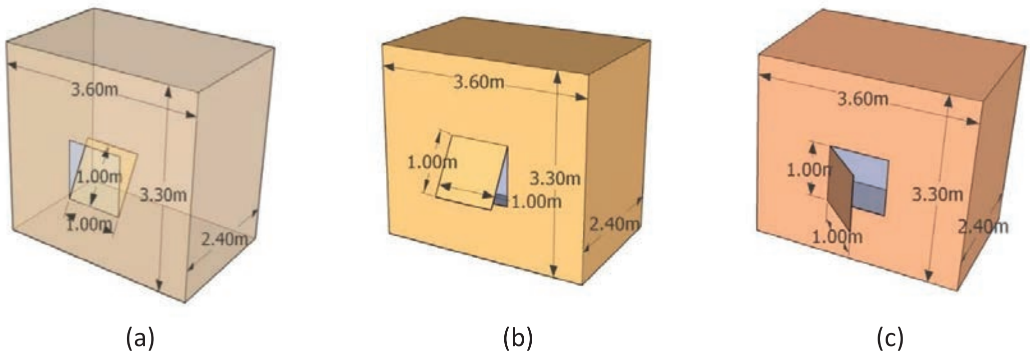

Fig. 4 Dimension of the simple building used in the CFD simulations (a) Hopper; (b) Awning; (c) Casement (rendered by Google Sketchup 8)

Table 1 Boundary conditions used in the CFD simulations for generating the database for the simple building

Case number	Window type	Opening angle	Incident angle	Averaged wind Speed at 10 m height (m/s)
2_1 to 2_10	Hopper	30, 45	0, 45, 90, 135, 180	3
2_11 to 2_20	Awning	30, 45	0, 45, 90, 135, 180	3
2_21 to 2_52	Casement	30, 45, 60, 90	0, 45, 90, 135, 180, 225, 270, 315	3

3. Results and Discussions

Due to the length of the paper, this section only shows the sample results of hopper, awning and casement windows.

Fig. 5 compares the predicted ventilation rate by proposed models with those simulated by CFD. The comparison indicated that the proposed models generally agree well with the CFD simulations. For hopper window, we observed over-predictions by the proposed model at 45° wind incident angle. The main reason is that the proposed model assumed the wind could still see the full hopper opening at all wind directions. However, at 45° only the normal wind component could see the full hopper opening. On the other hand, when the window was at the leeward side, the accuracy of the model improved because the opening was at the weak region and the flow is rotational due to the presence of the eddies. Since the rotational flow doesn't have specific directions, the model assumption becomes valid again at leeward conditions.

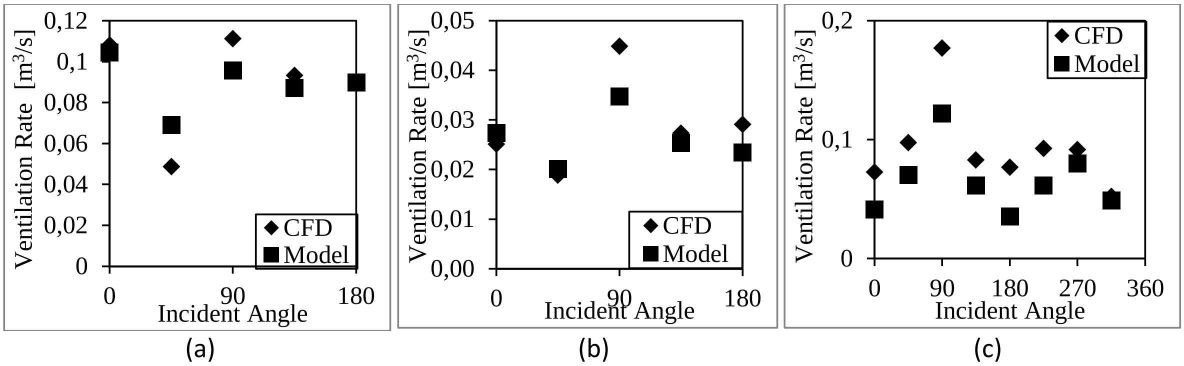

Fig. 5 Comparison of the ventilation rates by CFD simulations and the proposed models for 45° opening angles for (a) hopper; (b) awning; (c) casement windows

For awning and casement windows, the models assume the flow enter the room via two paths. While this is true for windward condition, at leeward condition, since the flow is less directional, the assumption might not be accurate. Therefore, we observed discrepancies when the wind is at leeward or parallel to the opening. Nonetheless, we could conclude that the models could give reasonable prediction compared to the CFD simulations for all three types of windows.

4. Conclusions and Future Work

This paper presented a systematic study on the impact of different window types on the ventilation rates caused by wind-driven, single-sided natural ventilation. The study led to the following conclusions:

- New semi-empirical models for hopper, awning, and hopper windows were developed to account for the impact of different window types on ventilation rate;
- The proposed model generally agreed with the CFD simulations with reasonable accuracy;
- For future study, the model could be validated by full-scale measurements to further exam the model's accuracy.

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