FURTHER DEVELOPMENT OF VENTIALTION WINDOW

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The study of ventilation windows for both natural ventilation and noise mitigation uses has drawn attention recently. It is challenging to design and evaluate the window performance by means of modelling and simulation. Here we present the numerical approaches to analyse and predict the thermal and acoustical performances of different window designs. By assuming typical flow and temperature conditions, the distribution of air velocity and temperature field in a representative residential unit is calculated using Computational Fluid Dynamics (CFD) method. The thermal comfort is evaluated using a static model based on the Predicted Mean Vote (PMV) method. As for the acoustic performance, the Sound Reduction Index (SRI) is studied by a proposed Finite Element Method (FEM) model, which is compliant with the ISO measurement standard in laboratory. Using the combined approaches, parametric studies are carried out based on a double-layer ventilation window configuration, where the effect of window opening sizes and the inlet flow conditions are investigated. It is found that the window design can provide enough fresh air, maintain adequate thermal and acoustical comfort by properly choosing the opening size. The feasibility of using a computational platform to evaluate and optimize ventilation windows is shown.

Keywords: natural ventilation, sound insulation, building acoustics, thermal comfort.

1. Introduction

Natural ventilation in residential buildings has a great potential for conserving energy and improving the health of occupants. However, its application is affected by many factors such as the outdoor climate condition, air pollution and environmental noise. To implement natural ventilation concept for residential buildings, the thermal comfort condition and the tolerable noise level for the occupants staying in the buildings need to be considered simultaneously [1, 2]. Barclay *et al.* [2] examined the traffic noise level in urban environment and proposed an integrated approach for combining noise exposure and ventilation performance together. By ensuring an acceptable noise level for the occupants, different cooling strategies can be adopted by rooms at different locations and orientations, resulting in 22% to 45% decrease in the required cooling energy.

As natural ventilation usually requires an open window, the combined sound insulation of the building façade is significantly deteriorated because of the opening. Literatures have shown that sound can easily transmit through an aperture with moderate size [3, 4]. If the acoustic comfort cannot be satisfied, people would more likely to close the window and turn on the air-conditioner. Thus, to ensure a successful implementation of natural ventilation technology, the acoustic performance of the adopted window design needs to be optimised.

In a recent paper, we demonstrate that improved sound insulation can be achieved by using double-layer window design [5]. The window openings on the first and the second layer are staggered, forming an S-shaped ventilation path. A prediction model for calculating the Sound Reduction Index (SRI) has been developed. In this study, we further develop our numerical platform to include both thermal and ventilation analyses. By assuming typical flow and temperature conditions, the distribution of air velocity and temperature field in a representative residential unit is calculated using Computational Fluid Dynamics (CFD) method, and the thermal comfort is evaluated using a static model based on the Predicted Mean Vote (PMV) method. The thermal comfort is then combined with acoustic comfort to assess the overall performance of the ventilation window. Following this introduction, the methodology for performing ventilation and acoustical simulation are presented in Sec. 2 and 3, respectively, and the numerical results are discussed.

2. Ventilation simulation

The ventilation analyses are carried out using commercial CFD software Fluent. Considering the ventilation window design as shown in Fig. 1(a), the window consists of two partially opened glazings, where the green arrow denotes the airflow path. To compare the ventilation performance with different opening size, three opening ratios are tested in the simulation, namely 1/2, 1/3 and 1/6 of the window area is opened. Note that for simplicity, the opening ratio of the first and the second window layer is kept the same.

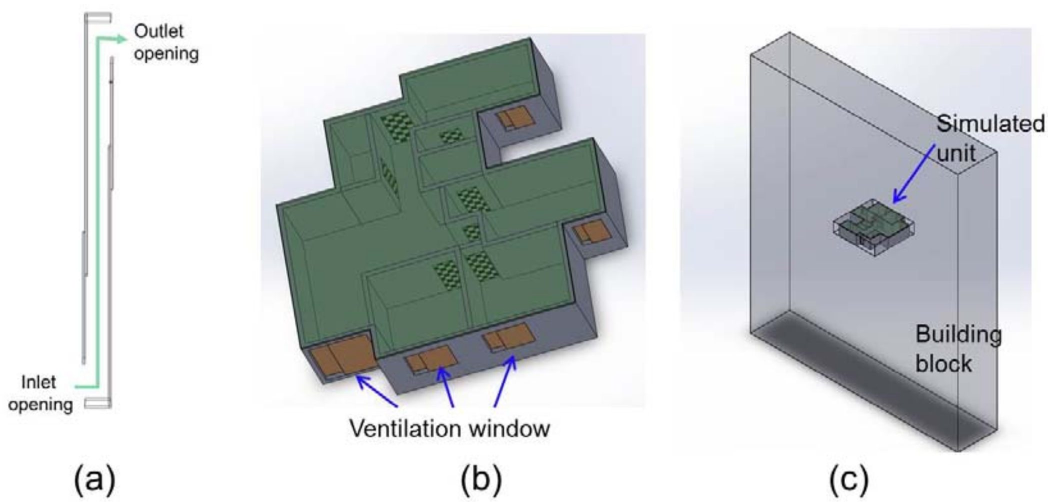

Figure 1: (a) Schematic of a double-layer ventilation window; (b) representative residential unit in Singapore mounted with ventilation windows; (c) location of the simulated unit in a building block.

Given a typical inlet flow condition, the interior flow and temperature field in a representative unit of Singapore [Fig. 1(b)] is simulated. In Fig. 1(c), the simulated unit is located at the centre of a building block. The effect of changing unit location to different building floors is considered, which is reflected by varying the inlet wind speed. In the simulation, six inlet wind speeds are selected as V_0 = 0.5, 1.0 and 1.7, 2.0, 2.6 and 2.93 m/s, corresponding to unit located from bottom to around twenty floors [6]. The inlet air temperature is assumed as T_{inlet} = 25 °C and all the initial temperature for the room walls are T_{wall} = 30 °C. The air velocity and the temperature distribution of the unit are obtained using a developed CFD model.

The thermal comfort index based on the PMV method is calculated as [7, 8]:

$$
\begin{aligned}
\mathrm{PMV} = & \left(0.303\mathrm{e}^{-0.036\mathrm{M}} + 0.028\right) * \{(M - W) \\
& - 3.96 * 10^{-8} * f_{cl} * [(T_{cl} + 273)^4 - (T_r + 273)^4] - f_{cl} * h_c * (T_{cl} - T_a) \\
& - 3.05 * 10^{-3} * [5733 - 6.99 * (M - W) - P_a] - 0.42 * [(M - W) - 58.15] \\
& - 0.0014 * M * (34 - T_a) - 1.7 * 10^{-5} * M (5876 - P_a)\}
\end{aligned} \tag{1}
$$

where M is the metabolic rate, (W/m^2). W is the effective mechanical power (W/m^2). I_{cl} is the heat insulation condition of the clothes (m^{2}K/W). T_{a} is the air temperature; T_{r} is the mean radiant temperature; and T_{cl} is the clothing surface temperature. V_{ar} is the relative air velocity (m/s); P_{a} is the water vapour partial pressure (Pa).

Figure 2 presents the simulation results. By defining the airflow as the air volume entering into the unit from the wind direction, the calculated airflow rate through the ventilation windows is shown in Fig. 2(a). It is observed that the airflow rate increases with a greater inlet wind speed V_0, and decreases with a smaller opening size, which is as expected. The averaged air speed over the entire unit, as plotted in Fig. 2(b), also shows a similar behaviour. The averaged air temperature in the room [Fig. 2(c)] decreases with a greater inlet wind speed and larger opening. This is because the simulation condition considers an incoming airflow with lower temperature to cool the room with higher temperature.

By using Eq. (1), the PMV value for every point inside the unit can be calculated from the velocity and temperature field. The comfort range is -1.0 < PMV < 1.0. To better assess the result, a ratio to describe the percentage of area which lies in the comfort range is defined. Figure 4(d) shows the variation of this ratio versus different wind speeds and opening sizes. It is found that the thermal comfort ratio increases from V_0 = 0.5 m/s and reaches the maximum at V_0 = 1.0 m/s. The highest value is obtained with V_0 =1.0 m/s and opening ratio of 1/6, where about 70% of the unit area is comfortable for the occupants. After that, the thermal comfort ratio decreases with increasing inlet wind speed, and such decrease is more rapid with larger opening ratio. To explain this, a closer look at the air temperature result at different window speed condition is presented in Fig. 2(e). The percentage of area with PMV<-1.0, namely the region where the occupants start to feel cold, increases rapidly with higher inlet wind speed. Smaller window opening size helps to reduce the cold area and maintain a satisfactory thermal condition. Figure 2(f) shows the distribution of PMV inside the unit at the condition V_0 = 1.0 m/s, window opening ratio=1/6. It is observed that the majority area of the unit is comfortable. Overall speaking, the CFD simulation indicates that it is possible to provide a comfortable thermal environment by using natural ventilation windows.

3. Acoustic simulation

Further to the ventilation analyses, the acoustic performance of the ventilation window is investigated. The SRI is used to describe the sound insulation, which can be calculated from the acoustic power reduction when sound passes through a window component. A simulation model based on two-dimensional FEM analysis has been developed. The simulation conditions comply with the ISO 10140 measurement standard in laboratory [9]. Figure 3 depicts the simulation model, where a point acoustic source is defined in a source room to generate acoustic excitation. The SPLs averaged in the source and receiving room, respectively, are subtracted to calculate the SRI (for details please refer to Ref. [5]).

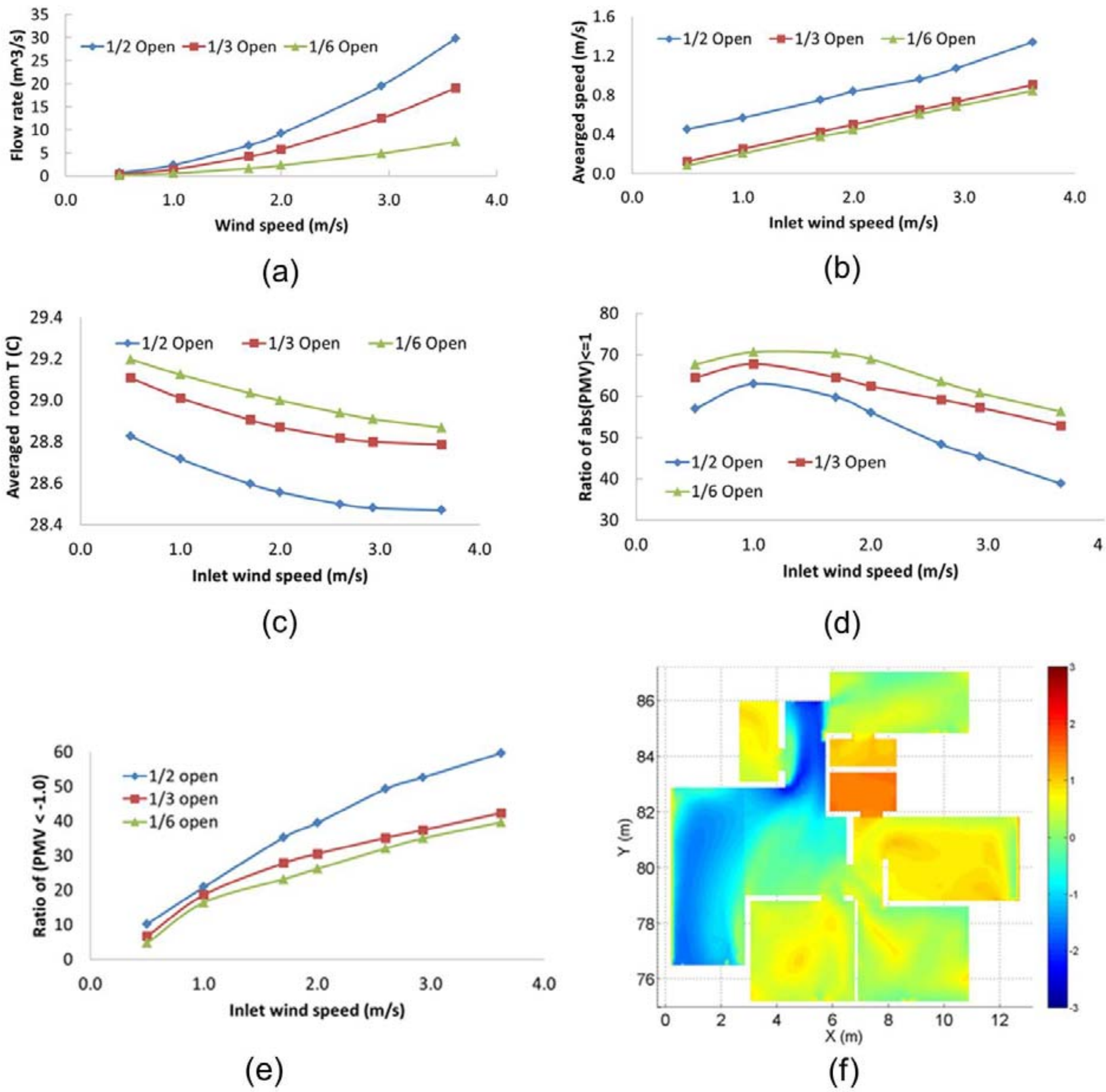

Figure 2: (a) Airflow rate versus inlet wind speed; (b) Averaged air speed over the unit versus inlet wind speed; (c) Averaged air temperature over the unit versus inlet wind speed; (d) Percentage of area with PMV<-1 versus inlet wind speed; (e) Distribution of PMV in the unit, V_0 = 1.0 m/s, window opening ratio=1/6.

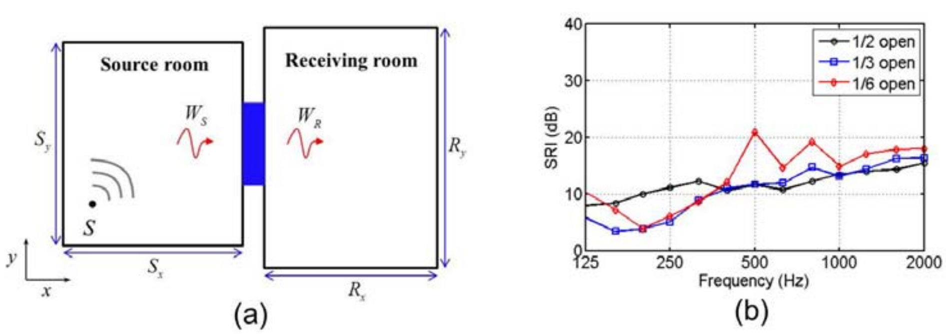

Figure 3: (a) Simulation model for SRI prediction; (b) Predicted SRI for three opening sizes.

The predicted SRIs for the three opening sizes are presented in Fig. 3(b) from 125 Hz to 2000 Hz. It is found that at frequencies higher than 300 Hz, smaller opening size leads to better sound insulation. The increment by narrowing the opening from 1/2 to 1/6 is generally 3 to 5 dB. At lower frequencies, the trend is reversed, possibly due to the diffraction effect which is more significant with smaller aperture size. The Single Number Rating (SNR) for the predicted SRI results, weighted by using ISO 717, is summarized in Table. 1 (C and C_{tr} are the adaptation terms for pink and traffic noises, respectively).

Table 1. Single Number Rating (SNR) for the predicted SRI results

Opening ratio	R_w	R_w+C	R_w+C_{tr}
1/2	14.3	13	12
1/3	14.8	14	12
1/6	16.5	15	13

The indoor noise level L_{in} can be estimated by using the following equation:

$$L_{in} = L_{out} - R + C_{room} \quad (2)$$

where L_{out} is the outdoor noise level reaching the façade of the building. C_{room} is the room correction factor related to the room size and room absorption, assumed as 2.4 dB for typical room condition [2]. R is the combined sound insulation of the façade, calculated as:

$$R = -10\log\left(\frac{S_r \times 10^{-\frac{SRI_r}{10}} + S_w \times 10^{-\frac{SRI_w}{10}}}{S_r + S_w}\right) \quad (3)$$

where r denotes the rigid building wall, w denotes the ventilation window. S_r, S_w are the corresponding area, SRI_r and SRI_w are the sound reduction index of the wall and the window, respectively. Here, a relatively rigid wall with SRI_r =50 dB is assumed, and the area ratio between window and building wall (exposed to noise) S_w / S_r is assumed as 1/3. The combined façade insulation with the ventilation windows is about 20 dB.

The feasibility of using the ventilation window for acoustic comfort is discussed. Assuming that an indoor noise level of 55 dB starts to cause annoyance to the occupants, the outdoor noise level (when using the ventilation window) should not be greater than 72 dB. This however may not be satisfied in some urban areas, especially near the trunk road [10]. For sleep comfort at night time, WHO suggests a noise level of 40 dB. The outdoor environmental noise for the ventilation window to be used should be less than 57 dB.

4. Conclusion

By combining the acoustic and CFD simulations together, we discussed the feasibility of achieving both acoustic and thermal comfort using natural ventilation windows. A typical residential unit of Singapore was used as an example in this investigation. The natural ventilation performance was simulated based on several inlet wind conditions, reflecting the variation of unit locations at different building levels. Several window opening ratios were considered. The flow, thermal and sound insulation performances of the simulated cases were compared.

Based on the simulation results, it was shown that natural ventilation is viable to provide adequate thermal comfort and noise insulation. The developed numerical approaches showed great potential to be used as efficient tools for better design and optimisation.

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