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Influence of Window Types on Natural Ventilation of Residential Buildings in Hong Kong

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ABSTRACT

Hong Kong is of subtropical climate where summer is hot and winter is warm. Natural ventilation is most desirable for cooling and providing fresh air in residential buildings in moderate seasons for better indoor air quality and thermal comfort. The natural ventilation performance is affected by a combination of internal and external factors. External factors include the location, the orientation, the prevailing wind speeds and the building forms of the residential development, which are subject to constraints beyond the control of site planners and architects. Whilst for internal factors like the openings configurations and window types, site planners and architects are always given free hand for a proper design. The influence of each of the internal factors on the natural ventilation performance is therefore of interest to them. As one of the studies on this topic, this paper focuses on the influences of window types on the natural ventilation of residential units in Hong Kong. On-site tracer-gas experiments and measurements were carried out in a representative residential unit with side-hung window. Based on the measured data, CFD software Airpak was used to simulate the natural ventilation performance for the use of different window types commonly adopted in residential buildings in Hong Kong, which are end-slider; side-hung; and top-hung windows. The ventilation effectiveness and the air distribution in indoor spaces were simulated and compared. The studied results provide useful information for future designs of residential buildings for better natural ventilation.

1. INTRODUCTION

The natural ventilation performance is affected by a combination of internal and external factors. External factors include the location, the orientation, the prevailing wind speeds and the building forms of the residential development, which are subject to constraints beyond the control of site planners and architects. Whilst for internal factors like the openings configurations and window types, site planners and architects are always given free hand for a proper design. Therefore research on influence of internal factors is especially significant to the designers.

Much literature on the influence of opening configurations on the ventilation performance can be found. They focus mainly on the opening combinations, area and relative locations, but rarely on the types of opening, i.e. the window types. For instance, Hassan et al (2007) investigated the effects of window combinations on ventilation characteristics in buildings by CFD simulation and wind-tunnel experiments; El-Agouz (2008) studied the effect of internal heat source and opening locations on natural ventilation. A conclusion was drawn that two openings with longer horizontal distance is better than shorter as far as single-sided ventilation performance is concerned. Additionally, Evola and Popov (2006) analyzed the wind driven natural ventilation in buildings by CFD-based programs. Three opening configurations, single-sided ventilation with an opening on the windward wall, single-sided ventilation with an opening on the leeward wall, and cross ventilation, were investigated. It was concluded that when dealing with single-opening ventilation, positioning the opening on the leeward side will result in a larger ventilation rate inside the building than on the windward side. With respect to opening area for cross ventilation, Tantasavasdi et al ( 2001) found that the ventilation performance is better with a larger inlet than with a larger outlet. It is noted that literature on opening configurations provided much information for the designers and researchers, but for window types, some are regarded as better than others just based on qualitative evaluation. Little works have been done so far to evaluate the quantitative difference in ventilation performance for the use of individual window types. Heiselberg ( 2001) investigated the characteristics of side-hung window and bottom hung window. It was concluded that both for the single-sided strategy and cross-ventilation strategy, the bottom hung window is better in winter as air needs to travel longer distance before reaching the occupied zone, while in summer, side-hung window is preferred to bottom-hung window in admitting enough air into the indoor space. Unlike the cold climate regions, the aim of ventilation in Hong Kong is season-independent. It is because the climate in Hong Kong is hot summer
and warm winter, natural ventilation as an efficient approach to improve indoor air quality is often aspired to get more. Hence, window design that can incur more natural ventilation is always preferred.

The aim of this study was focused on the influence of window type, such as top hung, side hung, and end-slider, on the natural ventilation performance of a residential unit in Hong Kong when taking into account the annual local wind environment. The objective was to figure out distributions of indoor mean air age under each condition, and then conclusions were drawn by comparison.

2. METHODOLOGY

In this study, the ventilation performance of a case study residential unit in Hong Kong with side-hung window was selected for site measurement and for CFD simulations. The site measurement was based on tracer gas decay method, while AIRPAK was used for CFD simulations. The mean air age was used to represent the ventilation performance. On satisfactory validation of the built model by the site measured results, the performance of three types of window to be incorporated into a case study unit was evaluated by CFD simulations. The three window types, namely: side-hung, top-hung and end-slider were selected because they are most commonly used in residential units in Hong Kong. The influence of window design on the ventilation performance was concluded based on the averaged air age of the case study unit under varying outdoor wind conditions.

2.1 Model Validation

2.1.1 Experimental measurement: To validate the simulation results, on-site measurement was conducted in a case study residential unit in Hong Kong. The front view and the layout of the unit are shown in Figure 1 and 2. It can be seen in Figure 1 that the case study unit is provided with side-hung windows. The unit was chosen for the following reasons. Firstly, the floor area of the case study unit, as highlighted in red in Figure 2, falls within the most common area range of residential units in Hong Kong which is between 60 and 90 m². Secondly, as shown in Figure 3 and Figure 4, the unit consists of four identical windows which is an ideal design for the study of the influence of changing opening area and window combinations on the natural ventilation performance, although this part of study will be reported in other papers by the authors. Thirdly, the estate where the case study unit was located is in a rather isolated site whereby there is virtually no external obstruction to introduce influences on the ventilation performance to enable a focused study on the influence of window types under varying wind conditions.
The site measurements were conducted on 17 and 18, November 2009. The measurement procedure was repeated on the second day (18 November) whereby the results were adopted in the subsequent analysis for more stable outdoor wind conditions.

CO2 was used as tracer-gas for its safety and low price as well as satisfying the accuracy requirement proved by other researchers (Roulet and Foradini 2000). The concentration decay method was adopted for the study of the air exchange performance in different study cases.

Four CO2 test points were positioned in the studied area as shown in Figure 4. Telaire 7001 CO2 monitors were fixed at 1.1m height at each point. The equipments were calibrated according to the user manual, and the accuracy was ±50 ppm.

According to the ASTM standards (2009), a portable meteorology station, as shown in Figure 5, was set up at the most unobstructed podium of the case study estate. Gill UVW Anemometer model 08274 was used to record the outdoor wind direction and velocity, while temperature and humidity sensors were used to record the air temperature and humidity. The sensors were located 11m above the ground floor. All the sensors were calibrated before usage and the accuracy were ±1%, ±0.3°C, and ±1.8% respectively. The results were used as the boundary conditions in the subsequent simulation investigations.

Mean Age of Air (MAA) was taken as an indicator of ventilation affectiveness for its wide application in similar studies (Sherman; Walker et al 1992; Gan 2000). It provides more meaningful information than the Air Changes per hour (ACH) in determining how “fresh” the air is at each studied points, rather than just one air change rate for a room.

The mean air age at a point can be calculated by an equation (ASHRAE 2002)

$$A_i = \frac{1}{C_o} \int_0^\infty C_i(t) dt$$

Where $A_i$ is the mean air age at a specific point, $C_o$ is the initial concentration of CO2, $C_i(t)$ is the concentration of CO2 at a specific point as a function of time, which can be obtained by regression of the measured values over the decay period.

2.1.2 Measurement results: The wind speed was fluctuating within a narrow range with a mean value of 2.3m/s, while the wind directions were mostly at 0 (360) degree to indicate that the prevailing wind was from north. This is normal for winter season in Hong Kong. The collected data was used in the CFD simulation as boundary conditions.

The mean air age at the four test points (T1 to T4 as shown in Figure 4) were measured. The calculated mean age of air and the simulation results are compared in a later session.
2.1.3 CFD simulation: Three dimensional (3D) actual size physical models for the residential building were established by Airpak. The upper part of the building was set transparent to clearly display the studied unit. The building is shown in Figure 6. The calculation domain was set as $5L \times 5W \times 3H$. This is to strike a balance in the computing capacity and the difference in results from an increased in domain; where $L$, $W$, and $H$ are the dimensions of the case study residential building. Considering the geometric shapes of most of the objects in the building, unstructured hexahedral mesher was used to create mesh; whilst the grids were refined at opening positions as large gradient may occur there.

The renormalization group (RNG) $k-\varepsilon$ turbulence model was used to simulate the steady state natural ventilation of the unit, and the airflow transport can be calculated by Equation (2):

$$\text{div} \left( \rho V \Phi - \Gamma_{\Phi,\text{eff}} \text{grad} \Phi \right) = S_{\Phi} \tag{2}$$

Where $\rho$ is the air density, $\Gamma_{\Phi,\text{eff}}$ is the effective diffusion coefficient, $V$ is the air velocity vector (m/s), $S$ is the source term of the general flow property, and $\Phi$ is any one of the components shown in Table 1. When $\Phi = 1$, the general equation becomes the continuity equation. The effective diffusion coefficient and the source terms for different $\Phi$ are also listed in Table 1. In the table, the effective viscosity $\mu_{\text{eff}}$ is the sum of molecular viscosity and turbulent viscosity. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-velocity coupling algorithm was used to discretize the controlling equations in AIRPAK. The solution was considered converged when the residuals of flow and energy were less than or equal to their specified convergence criteria, $10^{-3}$ and $10^{-6}$ respectively.

<table>
<thead>
<tr>
<th>Equations</th>
<th>$\Phi$</th>
<th>$\Gamma_{\Phi,\text{eff}}$</th>
<th>$S_{\Phi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Momentum</td>
<td>$U_i$</td>
<td>$\mu_{\text{eff}} / \sigma_k$</td>
<td>$P_k - \rho \varepsilon + G_k$</td>
</tr>
<tr>
<td>Turbulence kinetic energy</td>
<td>$k$</td>
<td>$\mu_{\text{eff}} / \varepsilon$</td>
<td>$\varepsilon(C_1 P_k - C_2 \varepsilon)/k + C_3 G_k \varepsilon/k - R_k$</td>
</tr>
<tr>
<td>Turbulence dissipation rate</td>
<td>$\varepsilon$</td>
<td>$\mu_{\text{eff}} / \sigma_T$</td>
<td>$S_T$</td>
</tr>
</tbody>
</table>

$P_k = \mu_1 \left( U_{i,j} + U_{j,i} \right) U_{i,j}, \mu_{\text{eff}} = \mu_i + \mu = C_\mu \rho k^2 / \varepsilon$

Where $\sigma_k, \sigma_\varepsilon, \sigma_T, C_1, C_2, C_3, C_\mu$ are constants

Boundary conditions were set according to the on-site measurement results, e.g. wind was coming from the north (the back of the building), with a velocity magnitude of 2.3 m/s. The air stream was taken as isothermal, because the temperature difference between indoor and outdoor in transition season is negligible in Hong Kong especially when the natural ventilation is stable after a long time. This is consistent with the measurement results. Therefore, the equation of energy conservation was not solved in the simulation, which can help improve the efficiency of solving other equations by saving the computing time and capacity.

2.1.4 Results of the model validation: The comparison of mean air age at the four test points is shown in Figure 7. It can be seen that the simulated results does not match perfectly with the site measurement results. The difference was between 3.4% and 34.5%. However, for both the site measurement and the simulation results, the MAA in the living room was found consistently smaller than the bedroom. Since the errors in similar cases are common in range of 10% to 50% (Zhao Z et al, 2007), and considering the wind was coming from the back of the building such that the case study unit was ventilated by the returning vortex flow, this simulation results is regarded as acceptable to conclude that the selected turbulence model and input boundary conditions are valid. Accordingly, it is reasonable to base on this model and the associated settings for further investigations.
2.2 Influences of window types

Three window types commonly used in Hong Kong were selected for further evaluations by simulations. This includes the side-hung, the top-hung and the end-slider types as shown in Figure 8 (a), (b) and (c). To evaluate the year-round ventilation performance for the use of different window types in the case study residential unit, three sets of prevailing wind directions and wind speeds concluded by analyzing the meteorological data of the typical weather year (TWY) of Hong Kong (i.e. 1989) were considered (where North is 0° and wind speed is in parenthesis). They were at clockwise 90° (3.7 m/s); 30° (2.42m/s); and 270° (1.97m/s). Their year-round frequency of occurrence is 57.4%, 13.9% and 13.8% respectively. With three window types and three wind conditions, nine cases were considered. The ventilation performance simulations were conducted based on the validated models.
3. RESULTS

The ventilation performance was also evaluated by MAA, and the distributions of MAA at 1.1m level of each case are shown in Figure 9. The color transition from deep blue to deep red indicated the MAA increases from 0 to 1500 seconds or above.

It can be seen in Figure 9 that the south-facing case study unit was best ventilated by the easterly wind; then was the westerly wind. The worst was the north-easterly wind no matter which type of window was used. Moreover, when wind was coming from the east (90°), the bedroom was better ventilated than the living room. Considering the frequency of occurrence of easterly wind in Hong Kong, it can be concluded that 57.4% of the time the bedroom is better in indoor air quality as far as air freshness is concerned. Same result was obtained for all three types of window. Additionally, for figures pertaining to the top-hung type (figures 9 (d), (e) and (f)), the red regions were more than other two window types under all window conditions (30°, 90°, and 270°), the side-hung was the second. In other words, end-slider window has the best performance; followed by the side-hung type, and the worst is the top-hung type.
To further quantify the difference in ventilation effectiveness by window types, MAA of the case study unit at three different levels of the four test points were extracted from the simulation results for a detailed analysis. The levels were 0.6m, 1.1m and 1.7 high above the floor of the unit, the four test points are shown in Figure 4, and the MAA values weighted by frequency of occurrence of different wind conditions (i.e. weighted averaged MAA) was used to represent the ventilation effectiveness. The 12 studied points were denoted by Tm,n, where ‘m’ denotes the position of the test point (1 to 4) and ‘n’ denotes the level (1= 0.6m, 2=1.1m, and 3=1.7m). The results are shown in Figure 10.
It can be seen in Figure 10 that the weighted averaged MAA of top-hung window is constantly higher than the others for all 12 studied points, which is 65.3% higher than that of the end-slider, whilst that of the side-hung window is also 17.2% higher than the end-slider window.

4. CONCLUSIONS

This study focused on evaluating the influences of window types on the ventilation performance of residential units in Hong Kong. On-site tracer-gas experiments and measurements were carried out in a case study residential unit with side-hung window. Based on the measured data, CFD software Airpak was used to simulate the natural ventilation performance for the use of different window types commonly adopted in residential buildings in Hong Kong, which are end-slider; side-hung; and top-hung windows. By simulation, the following conclusions were drawn:

(1) End-slider window performs better in admitting natural ventilation.
(2) The ventilation effectiveness of the end-slider window, represented by the weighted averaged MAA, was found 17.2% better than the side-hung window.
(3) The top-hung window is the worst in a natural ventilation effectiveness, and the weighted averaged MAA was 65.3% longer than that of the end-slider window.

The conclusions can provide useful information for building designers to make a residential building be more naturally ventilated, and hence energy conservation and comfortable. However, the conclusions were obtained by investigations based on weather conditions of Hong Kong, they are effective just in those area of similar climate as Hong Kong.

REFERENCES