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Optimization of window systems to achieve thermal comfort in the hot and humid climate of Indonesia

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SUMMARY

This paper aims to optimize the window systems to improve thermal comfort during the daytime in the hot and humid climates. We particularly analysed the effects of window type on indoor air flow pattern through CFD simulation and field experiment by using an experimental building in Indonesia. The performance of windows was assessed with SET* at the center of the rooms and convective heat transfer on the floor. The results show that the window types largely influence the air flow pattern in the occupied space (FL+1,100). In particular, in case of the horizontal pivot window, the reduction of SET* was by 0.30-0.79°C in the occupied space and the reduction of heat transfer coefficient on the floor was up to 1.52 W/m^2K, compared with the simple opening. The results indicate that the horizontal pivot window could provide sufficient ventilation and the structural cooling effect.

KEYWORDS

Window design, Natural ventilation, Thermal comfort, Tropics, Passive design

1 INTRODUCTION

Night ventilation with cooler outdoor air dissipates the heat from building structure, and thus, in a high thermal mass building, structural cooling through night ventilation can be effective even in the hot and humid climate. Meanwhile, a previous study has shown that even in modern houses across tropical Southeast Asia, most occupants tend to open windows to allow for ventilation during daytime, regardless of air conditioner (AC) ownership (Mori et al., 2018). Moreover, occupants tend to feel better thermal comfort satisfaction through the floor material with high thermal mass and high thermal conductivity. Therefore, maintaining the structural cooling effect during the daytime is important. In order to satisfy the thermal comfort of the occupants by natural ventilation during the daytime through the structural cooling effect, it is preferable to control indoor air flow by designing window system (Prianto and Depecker, 2003). This study aims to determine window systems that can optimize the indoor airflow pattern to achieve thermal comfort of the occupants, while maintaining the structural cooling effect in the daytime.

2 METHODOLOGY

In this study, the ventilation performance of window systems was examined numerically and experimentally by using an experimental building located in Tangerang, Indonesia. The experimental building has two identical rooms (A and B), and each room has the size of 4.98 × 5.15 m with the floor to ceiling height of 3m. To eliminate the thermal influences from the outdoors, external walls facing the East and West were installed with thermal insulation boards. The proposed window systems were installed on the wall of the northern side of the building, which is also the prevailing wind direction on the measurement site.

2.1 CFD simulation

The CFD simulation was conducted to optimize the indoor air flow pattern by using the above-mentioned building as a base model. A commercial software, scSTREAM v14 was used to solve the Reynols-averaged Navier-Stokes (RANS) equation. All cases were analysed under a steady-state with isothermal condition. The computational domain for the simulation was determined following the guidelines by Tominaga et al (2008). 5 H was set for the inflow boundary and 10 H for the outflow boundary where H is the height of the building. As for the turbulent model, standard k-ε model, which is the common model and can obtain an overall reasonable accuracy in the analysis of indoor flow pattern, was used in this simulation. For the inflow boundary, static wind velocity of 1.5 m/s was employed. This wind velocity represents the average daytime outdoor wind speed during field experiment. As shown in Figure 1, indoor air flow pattern and wind speed at the occupied space (FL+1,100) and near floor surface (FL+300) were investigated under several window systems which include the window type, angle of the window, aspect ratio of window and opening position for inlet and outlet opening. Throughout the cases, the area of opening was set to be 1.44 m^2.

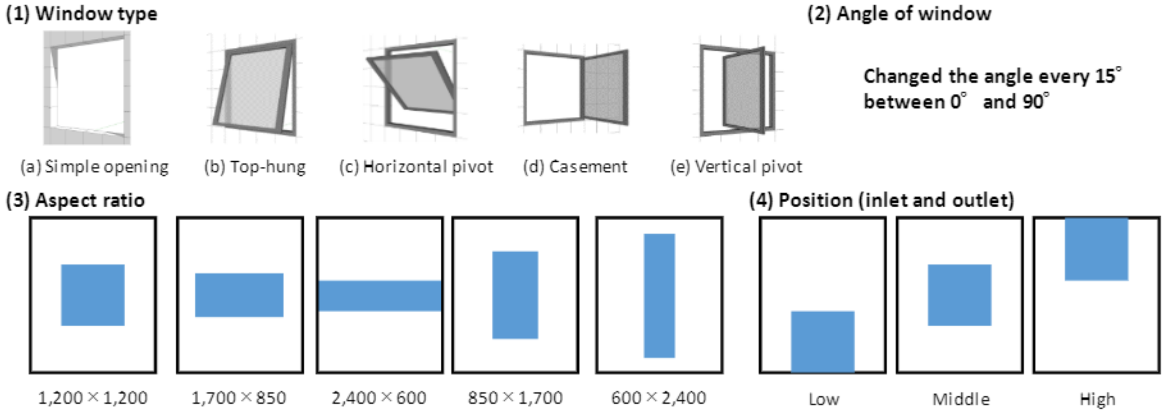
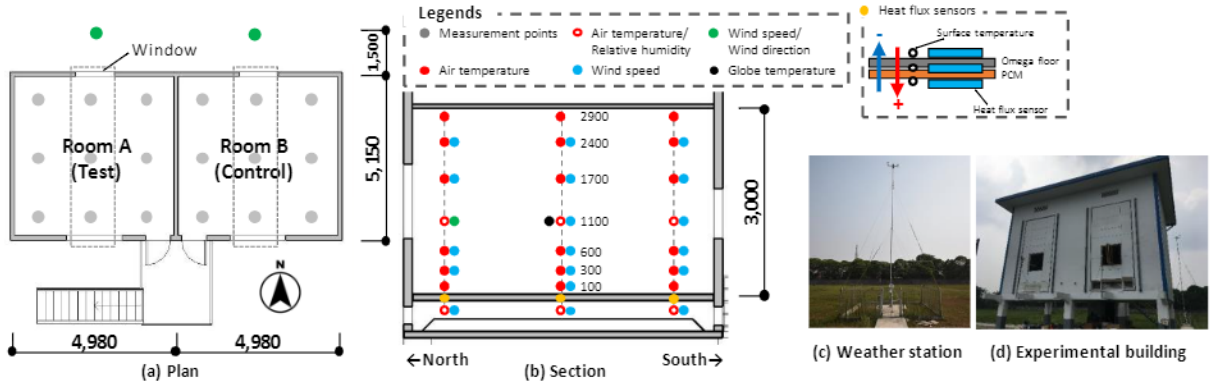


Figure 1. Parameters of opening for the simulation.



(a) Plan (b) Section (c) Weather station (d) Experimental building

Figure 2. Experimental rooms and settings.

2.2 Field experiment

Field experiments were conducted to identify effective window systems under natural ventilation condition as well as to verify the result from CFD simulation. Based on the results of preliminary CFD simulation, three cases were selected as listed in Table 1. The effect of the window system on the improvement of thermal comfort was investigated by comparing Room A (test) with B (control) for each case respectively. Room A was equipped with a floor cooling system using phase change material (PCM). Data used in the analysis were collected from three continuous sunny days. All cases were conducted under full-day ventilation.

Table 1. Experimental cases.

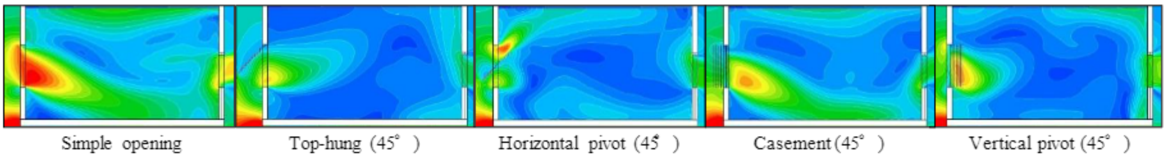
Case	Room A (Test)		Room B (Control)	
	Window type	Opening ratio	Window type	Opening ratio
Case 1	Top-hung (45°)	1,200 × 1,200	Simple opening	1,200 × 1,200
Case 2	Horizontal pivot (90°)	1,200 × 1,200	Simple opening	1,200 × 1,200
Case 3	Horizontal pivot (90°)	2,400 × 600	Simple opening	2,400 × 600

3 RESULTS AND DISCUSSION

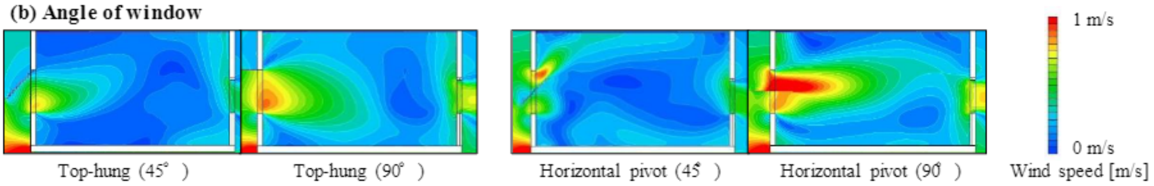
3.1 Indoor air flow pattern calculated by CFD simulation

Figure 3 (a, b) presents the indoor air flow patterns resulted from the CFD simulation on the tested window systems. As shown in Figure 3a, when the wind reaches the outer wall, the wind diverges from a stagnation point and the wind goes downward at the height of the opening. In case of the simple opening and the casement window (45°), they bring 1.1 to 1.3 times higher wind speed to the space near the floor surface than the occupied space at the middle of the room. In contrast, the top-hung window and the horizontal pivot window change the vertical air flow pattern regardless the inflow direction. In particular, the top-hung window and the horizontal pivot window with 90° opening angle could let the wind pass through the occupied space. At the middle of room, the wind speeds at FL+1,100 resulted from the top-hung (90°) and horizontal pivot (90°) are 0.35 m/s and 0.34 m/s, respectively. Meanwhile, those on the near floor surface are 0.28 m/s and 0.21 m/s respectively.

(a) Window type



(b) Angle of window



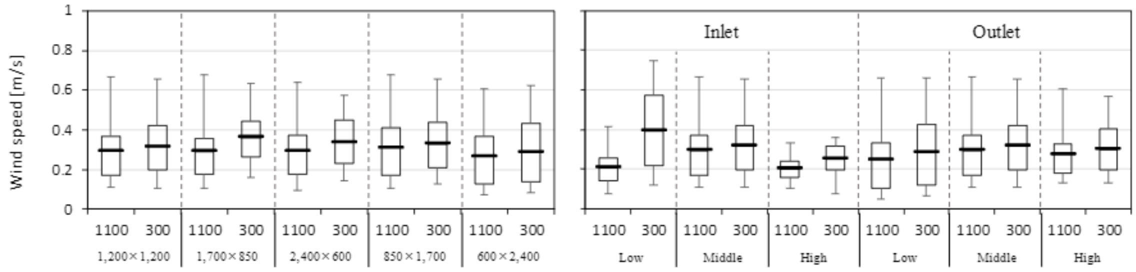

(c) Aspect ratio **(d) Position (Inlet and Outlet)**

Figure 3. (a, b) Vertical air flow pattern at the middle of room; (c,d) the average wind speed at the occupied space (FL+1,100) and near floor surface (FL+300).

Figure 3c and 3d show the wind speed ranges at FL+1,100 and FL+300 under different aspect ratio and the position of the opening, respectively. As shown, the impact of the aspect ratio is relatively small on average wind speed. Nevertheless, in case of 4:1 (horizontally wide opening), the wind speed ranges near the floor surface space are slightly narrower if compared to the aspect ratio of 1:4 (long vertical opening). Regarding the effect of opening position, opening at the center of the wall presents the best wind speed ratio (i.e. the ratio of the average wind speed at the occupied space to that near the floor surface) of 0.93, although the inflow wind goes downward reaching the near floor surface of the room.

3.2 Verification of indoor air flow under field experiment

Average outdoor air temperature during the daytime of field experiment ranged from 30.1-32.0°C. The average diurnal outdoor wind speeds for Case 1, 2, and 3 were 1.00 m/s, 1.85 m/s, and 1.63m/s, respectively. The prevailing wind was from North and South during the daytime and night-time, respectively.

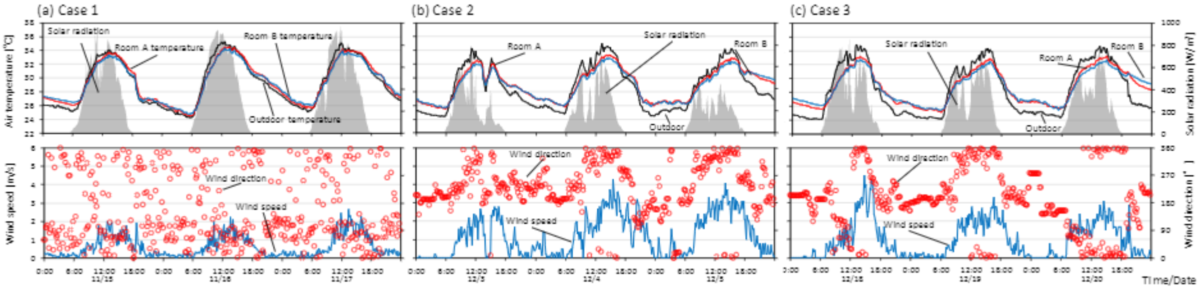


Figure 3. Temporal variations of the measured air temperature in the experimental facility and the corresponding outdoor conditions (a) Case 1; (b) Case 2; (c) Case 3.

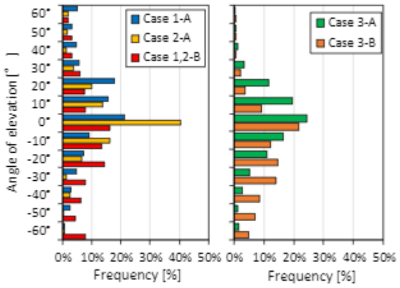


Figure 5. Frequency of inflow elevation

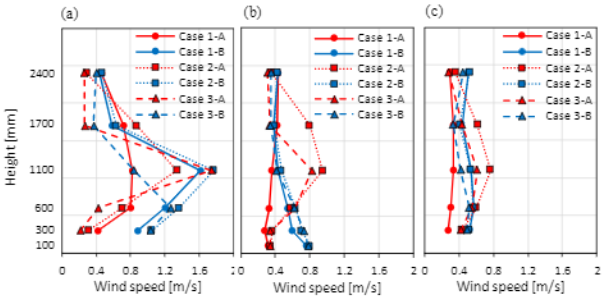


Figure 6. Vertical distribution of wind speed at (a) windward side; (b) middle; (c) leeward side in Room A and Room B

Figure 5 shows the frequency of inflow wind elevation, while Figure 6 shows the vertical distribution of wind speed at the windward side, middle of the room, and leeward side, respectively. As shown from the result in Room B, the wind through the opening mostly went downward (account for 54-61% of the time). This agrees with the CFD simulation result. The highest wind speed in Room B was observed at FL+100 at the middle of the room. Based on the measurement results in Room A, it is apparent that the window type strongly affects the indoor air flow pattern. In Case 1, the top-hung window controlled the air flow towards upper space of the room and 73% of inflow passed straight or upward. In case of the horizontal pivot window (Case 2 and 3), the occupied space (FL+1,100) experienced the highest wind speed among other vertical measurement points. In particular, the horizontal pivot windows gave 2.4-2.6 times higher wind speed to the occupied space than to the near floor surface regardless of the inflow wind direction. In Case 2, 40% of inflow went straight and relatively strong wind reached the occupied space of the leeward side with the wind speed of 0.77 m/s. These results indicate that the horizontal pivot window could contribute to the improvement of thermal comfort, while keeping structural cooling effect since this window type could provide relatively high wind speed to the occupied space while distribute lower wind speed near the floor which could reduce the convective heat transfer on the floor during the daytime.

3.3 Evaluation of indoor thermal comfort at the occupied space

The influence of window types on indoor thermal comfort was evaluated using SET*. The data from the field measurement was used in the thermal comfort evaluation. ASHRAE (2017) indicates the thermal environments can be regarded as acceptable if more than 80% of occupants feel it acceptable. Upper comfort SET* limit in the naturally ventilated houses in the tropics was set to be 29.9°C (Nguyen et al. 2012).

Figure 7 shows temporal variation of SET*, calculated using the measured data at 1.1 m height above the floor in the center of the rooms. In Case 1 (top-hung window), SET* in Room A was 0.50-0.67°C higher than that in Room B (Simple opening). This is because the corresponding air temperature in Room A was 0.25-0.32°C higher than in Room B. Moreover, it is presumed that Room A received 0.11-0.16 m/s lower wind speed compared with Room B due to smaller effective opening area. The top-hung window is commonly used for the buildings in Indonesia, therefore it is difficult to achieve the required thermal comfort using natural ventilation in building with top-hung window. Meanwhile, in daytime of Case 2 (Horizontal pivot), the average SET* ranged from 28.7-29.9°C in the daytime and more than half period of the daytime could meet the acceptable thermal comfort range. In particular, in the third day of Case 2 measurement, the thermal discomfort period was very small, which was only 15% of the day, mostly due to the high outdoor wind speed (2.3 m/s on average). Similarly, in Case 3 (horizontal pivot with aspect ratio of 4:1), the daytime SET* in Room A was reduced by 0.30-0.79°C, comparing with the corresponding SET* in Room B. The acceptable period in Case 3 ranged from 64-78%.

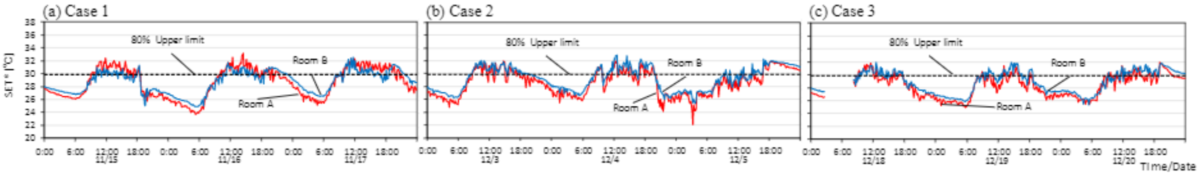


Figure 7. Temporal variation of SET* (a) Case 1; (b) Case 2; (c) Case 3.

3.4 Investigation on retention of the structural cooling effect on the floor

As discussed above, the daytime ventilation can diminish the nocturnal cool storage due to the daytime heating effect. Therefore, the heat transfer coefficient which influences the retention of structural cooling effect was analysed. The heat transfer coefficient was calculated by using Equation (1).

$$\alpha = \frac{Q}{T_a - T_s} \tag{1}$$

where α is the heat transfer coefficient, Q is the heat flux, T_a is the air temperature at the vicinity of floor and T_s is the surface temperature of floor. Figure 8 shows the comparison on the heat transfer coefficients. The measured heat transfer coefficient ranged from 2.37-26.8 W/m^{2}K. This wide range of the heat transfer coefficient is largely influenced by the wind speed during measurement. In Case 1 (Top-hung window), the maximum heat transfer coefficient in Room B was 21.3 W/m^{2}K and it was 2.22 W/m^{2}K higher than that of in Room A, nevertheless the average heat transfer coefficient is similar in the both rooms (around 9.4 W/m^{2}K). This is because the analysis of heat transfer coefficient considered both winds from the north and south and the inflow of simple opening on south side influenced the results of the heat transfer coefficient. However, in the afternoon, when the wind speed is relatively strong, the prevailing wind direction is mainly from the North. Therefore, the maximum heat transfer coefficient was affected by those wind conditions. In Case 2 and 3 (Horizontal pivot window), the winds are mostly coming from the north during the daytime. The average heat transfer coefficient ranged from 9.48-9.65 W/m^{2}K (Room A) and 10.4-11.0 W/m^{2}K (Room B) respectively. The maximum values in Room A were smaller than those in Room B as well. This indicates that the horizontal pivot window can reduce the convective heat transfer on the floor, thus influences the retention of structural cooling effect in the daytime.

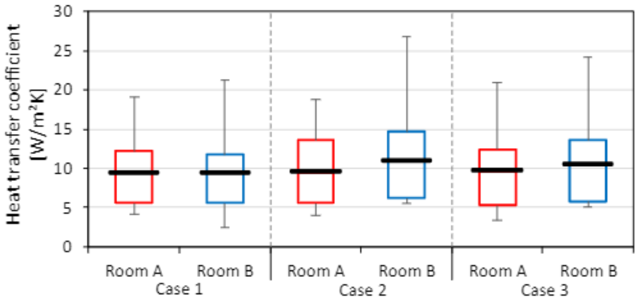


Figure 4 Measured heat transfer coefficient on the floor.

4 CONCLUSIONS

CFD simulation and field measurement were carried out to investigate the indoor air flow pattern as well as to evaluate the indoor thermal comfort resulted from various window systems for the hot and humid climate. The horizontal pivot window (with 90° opening angle) brought up to 1.6 (based on CFD simulation) and 2.6 (based on the field experiment) times higher wind speed to the occupied space (FL+ 1,100) than to the floor-level space (FL+ 300) regardless the outdoor wind direction. Moreover, the horizontal pivot windows could lower the SET* by 0.30-0.79°C in the occupied space, compared with the simple opening. Moreover, the horizontal pivot window could lower the heat transfer coefficient up to 1.52 W/m^{2}K. This indicates that the horizontal pivot window can improve the thermal comfort, i.e. lowering the SET* at the occupied space and the heat transfer coefficient on the floor, under the natural ventilation model in the tropics.

5 ACKNOWLEDGEMENT

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