THE EFFECTS OF BALCONIES ON THE NATURAL VENTILATION PERFORMANCE OF CROSS-VENTILATED HIGH-RISE BUILDINGS

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ABSTRACT

Natural ventilation performance can be influenced by various factors, including facade treatments such as balconies. Balconies have been commonly incorporated into residential buildings for various purposes, yet the provision of a balcony as a passive design strategy to improve natural ventilation is not one of its common purposes. The objective of this study is to investigate the effect of balcony design on the natural ventilation performance of cross-ventilated high-rise apartments. This study uses Computational Fluid Dynamics (CFD) models to predict ventilation performance. CFD models are selected because of their accuracy, flexibility and ability to provide comprehensive data for the investigation. This study suggests that balconies in high-rise apartments could improve the ventilation performance of high-rise apartments, but that balconies can also have a negative impact on ventilation performance if not appropriately designed. Finally, this study suggests that balconies could improve the level of thermal comfort and indoor air quality of apartments by providing greater indoor air speed and better ventilation performance, respectively.

KEYWORDS

high-rise building, cross ventilation, balcony, computational fluid dynamics (CFD)

1. INTRODUCTION

Natural ventilation is a solution for housing sustainability that can reduce housing energy consumption, which depends on mechanical ventilation and air-conditioning to provide indoor thermal comfort and air quality. Optimising the natural ventilation performance in high-rise residential buildings using a readily available prevailing wind can improve indoor thermal comfort, and appropriate passive design solutions along with greater awareness among building occupants can contribute to a significant energy reduction. Reducing energy demand is crucial in high-rise residential buildings because the energy efficiency in such buildings is much lower than that in a typical detached house (Blundell, 2010). Therefore, it is important

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to understand the potential of natural ventilation in high-rise residential buildings to ensure that the advantage of a higher wind speed around high-rise buildings is optimised for thermal comfort and indoor air quality, which subsequently reduces the energy consumption of the buildings.

Two natural ventilation strategies exist: single-sided and cross ventilation. In order to differentiate these types of ventilation strategies, simple definitions for single-sided and cross ventilation are used. For an apartment with a simple rectangular shape, such as in this study, single-sided ventilation is defined as a condition where one or more openings exist only in one façade, whereas, for cross ventilation, two or more openings exist in any combination of two or more façades (Mohamed et al., 2011b).

Between the two strategies, cross ventilation is the preferred ventilation strategy and is known to be significantly more effective. The effectiveness of the cross ventilation strategy leads to its common application in high-rise residential buildings. However, the potential of natural cross ventilation in high-rise buildings has yet to be fully optimised with appropriate passive design solutions.

Various studies have been conducted to investigate the natural ventilation performance in high-rise residential buildings, such as those by Cho et al. (2012), Prajongsan and Sharples (2012); Ismail (1996) and Sapian (2003). The study by Prajongsan and Sharples (2012) shows that ventilation shafts can be introduced in single-sided ventilation high-rise residential buildings to improve indoor air velocities where the ventilation shafts could become an effective wind-induced ventilation system for creating cross ventilation in single-sided residential unit. The study by Cho et al. (2012) has shown that in a single-sided ventilated room in high-rise residential buildings, the configuration of openings affects the indoor ventilation performance of the room. The study by Cho et al. (2012) also stated that the efficiency of cross ventilation strategy is much greater than the single-sided ventilation strategy. While Cho et al. (2012) and Prajongsan and Sharples (2012) investigated the potential of a single-sided strategy, Ismail (1996) and Sapian (2003) focused on strategies to improve cross ventilation strategy.

The study by Ismail (1996) has shown that wind-driven natural ventilation is feasible to improve thermal comfort in high-rise buildings. The study compares various building configurations, including the effects of the introduction of protrusion elements on high-rise buildings. Based on the completed wind tunnel experiments, the study demonstrates that a simple introduction of a 1.5 m protrusion does not significantly affect the wind pressure distribution on the facade of the tested models except at the downwind corner for an oblique wind angle. Therefore, using an empirical model (pressure difference method) to predict the ventilation of the buildings, the study suggests that introducing protrusion elements on the facades of a building does not significantly change the cross-ventilation performance of the buildings except under an oblique wind angle.

Sapian (2003) investigated the effects of introducing voids to improve the cross-ventilation performance for high-rise residential buildings with a focus on low cost housing type. The study shows that the net effect to the vertical distribution of wind pressure on windward and leeward facade is insignificant, which suggests that if a cross ventilation strategy is applied, the ventilation performance may not change significantly. Sapian also stated that the most affected levels are those located above the voids that result in a greater pressure difference between the windward and leeward walls, which means that the cross ventilation for units above the void can be improved.

The two examples by Ismail (1996) and Sapian (2003) show that the potential of the cross-ventilation strategy in high-rise buildings can be enhanced by providing appropriate passive design solutions. The provision of protrusion elements and the introduction of voids are two of the potential passive design solutions that could improve indoor ventilation performance. Between the two, the authors of this paper are interested in extending the investigation by Ismail by introducing a protrusion element that resembles a balcony. This study is also a continuation of an earlier study by the authors (Mohamed et al., 2011a) that focuses on the effects of balconies in high-rise apartments. The earlier study was limited to investigating the wind pressure distribution on the facades of the buildings and provided a simple discussion on ventilation performance and indoor airflow pattern. The current study further extends the previous study by including a more detailed discussion of the indoor ventilation pattern and ventilation rate under various balcony and opening configurations. Understanding that a balcony can improve ventilation performance is important because balconies are becoming more common on high-rise residential buildings due to their various benefits, as discussed by Papamanolis (2004) and Mohamed et al. (2008).

A balcony is defined as "a platform that is built on the upstairs outside wall of a building, with a wall or rail around it; you can get out onto a balcony from an upstairs room" (Hornby, 2000) or "a platform projecting either from an inside or an outside wall of a building" (Cowan and Smith, 2004). Balconies make various contributions to sustainable development, including the potential to induce natural indoor ventilation. Openings provided at the façade of apartments also play a significant role in inducing indoor air flow. Appropriate allocation of openings in response to changes in the pressure distribution created by balconies can improve indoor air flow. Factors affecting indoor air flow in relation to openings are the size, type, position, and number of openings as well as the distance between openings (Allard, 1998, Prianto and Depecker, 2003, Prianto and Depecker, 2002, Givoni, 1976). In the case of balconies, there is an advantage to having a large total area of openings that include both windows and doors to allow the occupants to access the balcony. These large openings allow for greater ventilation potential and flexibility to control ventilation performance in the apartment. An example of a successful application of balconies as a passive design strategy to induce indoor ventilation performance is their application in the 21-storey Menara UMNO designed by Ken Yeang, a famous architect in green building design (Ivor, 2001). Other than the completed tower by Ken Yeang, no academic studies have focused on the effects of various balcony configurations on the cross-ventilation performance of high-rise buildings. Therefore, the objective of this study is to investigate the effect of balcony design on the natural ventilation performance of cross-ventilated high-rise residential buildings.

2. METHODOLOGY

This study uses CFD commercial software as the tool for the investigation. Because the results obtained using CFD models are difficult to assess, wind tunnel tests are commonly used to validate CFD results (ASCE, 2003, Chen, 2009). The combination of CFD models as a main tool and wind tunnel tests for validation has been applied by many researchers, such as Sapian (2003), Cheng (2006) and Ai et al. (2011). In this study, data from a completed wind tunnel experiment (Ismail, 1996) are used for validation. The experiment by Ismail is selected because the dimension of the investigated building model is a high-rise building model that is also appropriate for this study, and the experiment provides complete wind pressure data on windward and leeward walls of different facade treatments for a high-rise building model. Thus, the data from the experiment is appropriate to be used in a validation study.

$$Q = C_d A_1 (2\Delta p/\rho)^{1/2} \quad \text{(Equation 1)}$$

where

Q = Ventilation rate (m^3s^{-1})
A_1 = Opening area, refer to Eq. 2 (m^2),
V = Wind speed (ms^{-1})
C_d = Opening discharge coefficient (dimensionless).
Δp = Pressure difference (Nm^{-2})
ρ = Air density (kgs^{-3})

$$1/A_1^2 = 1/(A_{in} + A_{out})^2 \quad \text{(Equation 2)}$$

where

A_{in} = Inlet opening area (m^2)
A_{out} = Outlet opening area (m^2)

Equation 1 is used to predict the ventilation rates during the validation. The value of 0.65 is applied as the opening discharge coefficient because the wind angle used in the validation study is limited to perpendicular wind (0°) only, and the opening size is less than 10% of the facade (Aynsley et al., 1977).

3. THE CFD MODEL

3.1 Building Form

Wind tunnel experiment data that are used for validation were obtained at an open-circuit wind tunnel facility at the University of Wales College of Cardiff (Ismail, 1996). The model's scale factor is 1:200. The intended real building size is 12-storeys with 4.0-m floor to floor height. There are 3 apartment units on each floor. The overall dimension of the building is 30 m (width) x 50 m (height) x 10 m (depth); thus, the floor area of each unit is 100 m^2. Two facade treatments are selected: a flat facade and a facade with 1.5 m deep balconies (Fig. 1). In the wind tunnel test, a total of 72 pressure taps are located in the middle of each unit (for both windward and leeward façades) along 6 vertical lines noted as A, B, C, D, E and F (Fig. 1 and Fig. 2).

Fig. 3 shows four different facade configurations, where Model S01 is the simplest facade treatment. Model S01 has a flat facade with an opening at two opposite external walls. The other models are modifications of Model S01. Models S02 and S03 have opening configurations similar to those of Model S01; however, balconies are introduced. The purpose of Model S02 is to investigate the changes of the cross ventilation performance of Model S01 that resulted from the introduction of balconies. In Model S03, the depth of the balconies is doubled to 3.0 m to investigate the effects of balcony depth.

In Model S04, the depth of the balconies is similar to that of Model S02, but instead of positioning the two openings in the middle of two opposite walls, the openings in Model S04 are arranged diagonally on the two opposite walls. The openings are located near the vertical protrusions of the balconies. The purpose of Model S04 is as a comparison to Model S02 where it investigates the effect of similar balcony configuration, but openings are located close

FIGURE 1. The front elevation of 12-storey building models (without opening) with 1.5-m vertical and horizontal protrusions. Each dot on the façade indicates the location of the pressure taps.

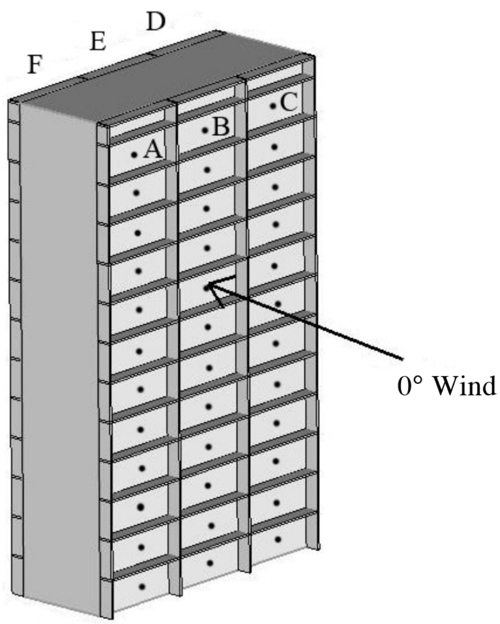


FIGURE 2. Wind direction (0°) and the position of tapping points for the model with balconies. For the other wind models, the model is rotated clockwise.

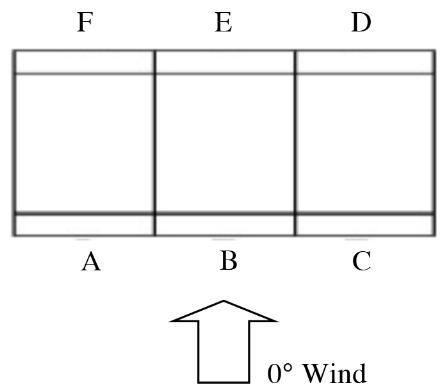
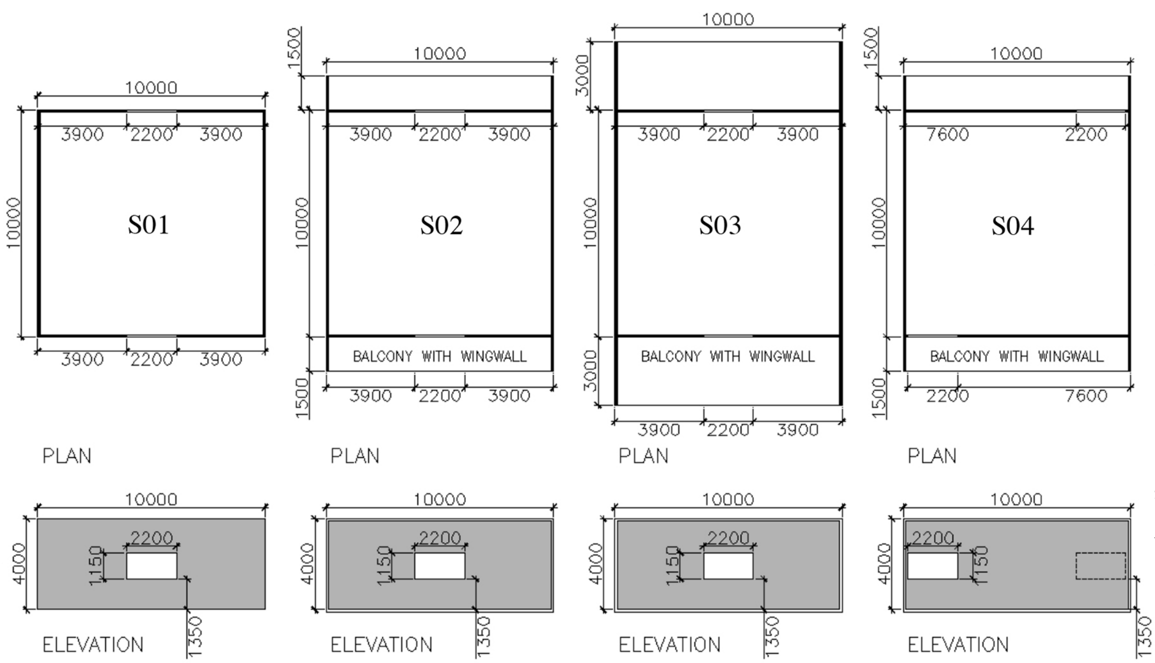


FIGURE 3. Four model configurations (S01 to S04) investigated in this study (in millimetres).



difficulties to converge due to the complexity of the building models with balconies. Thus, the factor of turbulence models is a limitation of this study.

The tetrahedron element is selected as the main mesh because of its robustness: it can be applied to complex building configurations, such as those in the subsequent coupled CFD simulations. A mesh independence study has been completed for a flat facade model and a model with balconies but limited to outdoor airflow only where predicted wind pressures are compared to the wind tunnel data. The tested number of elements range between 0.5 million to 17.5 million. The number of elements of 3.9 million for flat façade and 10.3 million for façade with balconies are selected for the validation study since these numbers do not give significant result differences compared to the setups with a greater number of elements.

The downstream distance is set to 500 m (or 10 times the building height) as recommended by Tominaga et al. (2008). Straw (2000) and Yang (2004) have adopted this distance in their studies. The outlet is set to a zero static pressure outlet boundary condition, similar to that used in studies by Cheng (2006) and Yang (2004). For upstream distance, appropriate distance shall be tested where according to the study by Cheng (2006), upstream distance influence the predicted air speed values close to the windward facade. In this study, multiple distances are tested and the distance of 60 m is found to be the most accurate. The inlet atmospheric boundary layer wind profile is similar to the wind tunnel experiment, which uses the power-law model with a mean speed exponent of 0.28. The wind speed at 10 meters high is 1.0 ms^{-1}. The wind direction tested for the outdoor airflow simulation is 0°, as shown in Fig. 4.

In the case of blockage ratio, it is set to be 1.875% which is less than the maximum blockage ratio of 3% as recommended by Franke et al. (2004) and Tominaga et al. (2008). The selected turbulence model for the simulation is the standard k-epsilon. The turbulence model is selected due to the complexity of the building models and selected coupled CFD simulation approach, where the turbulence model is more universal, consistent and stable, though it may perform more poorly in some cases (Malkawi and Augenbroe, 2003). It is a recommended model for general purposes (Srinivasa, 2010), and it is one of the two most common models in the prediction of airflow for buildings (Chen, 2009, Li et al., 2005). The final CFD setups for the outdoor airflows can be observed in Table 1.

For the coupled CFD simulation, similar to the outdoor airflow simulation, tetrahedron and prism meshes are applied but with inclusion of internal tetrahedron meshes. Therefore,

FIGURE 4. The CFD domain for the models at 0° wind angle (for CFX).

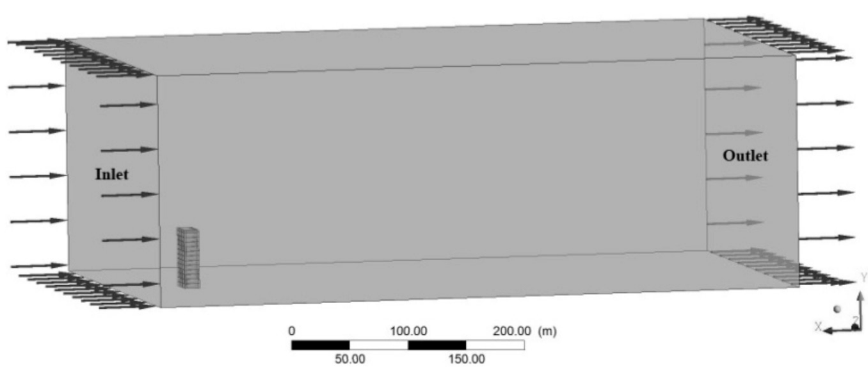


TABLE 1. The CFD setups for outdoor only airflow.

	SETUP
Software	CFX
Upstream distance	60m
Downstream distance	500m
Mesh type	Tetrahedron and prism (on the ground surface only)
Number of element (maximum)	Approximately 3.9 million (Flat facade) and 10.3 million (facade with balconies)
Turbulence model	The standard k-epsilon
Blockage ratio	1.875%

the maximum total number of elements is approximately 24 million. The inlet distance, downstream distance, turbulence model and the blockage ratio remain the same as those listed in Table 1. In addition to a 0° wind angle, 45° and 90° angles are also tested for the coupled CFD simulation.

4. CFD VALIDATION STUDY

The validation study is completed in two stages: outdoor airflow and coupled outdoor and indoor air flow. To validate the outdoor airflow, the wind pressure distributions predicted by the wind tunnel experiment and CFD simulation are compared. To validate the ventilation rate, the following approaches are compared:

- Approach 1: Coupled CFD simulation.
- Approach 2: Combination of Wind Tunnel experiment (wind pressure data) and Empirical models (Equation 1)
- Approach 3: Combination of outdoor only CFD simulation (wind pressure data) and Empirical models (Equation 1)

Approach 1 is the coupled CFD simulation that simultaneously simulates the outdoor and indoor airflow. In the case of the other approaches, wind pressure distribution data are obtained from either wind tunnel experiments or CFD outdoor airflow simulations; then, the wind pressure data are used to predict the ventilation rate using Equation 1. Discussion on these approaches can be found in Mohamed et al. (2013).

Fig. 5 and Fig. 6 compare the wind pressure distributions for pressure taps along Line B and E using CFD with those of existing wind tunnel data. Table 2 and Table 3 compare average wind pressures along Line A to Line E. It can be observed that the wind pressure predictions for CFD are acceptable for the windward facade of the models with and without balconies. However, for the wind pressure distribution on the leeward side, the predictions by CFD are found to be over-predicted, especially at the bottom of the facades. Less accurate prediction on the leeward side is expected due to the application of the k-epsilon models. Similar findings were observed in the studies by Tsuchiya et al. (1997), Straw (2000) and Yoshie et al. (2007).

FIGURE 5. Comparison of wind pressure distributions on windward facades along Line B for facades with and without balconies at a wind angle of 0°.

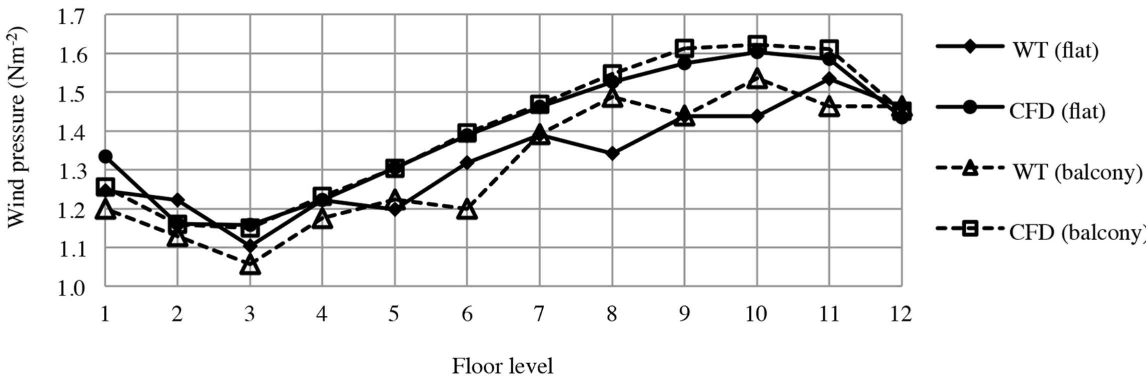


FIGURE 6. Comparison of wind pressure distributions on leeward facades along Line E for facades with and without balconies at a wind angle of 0°.

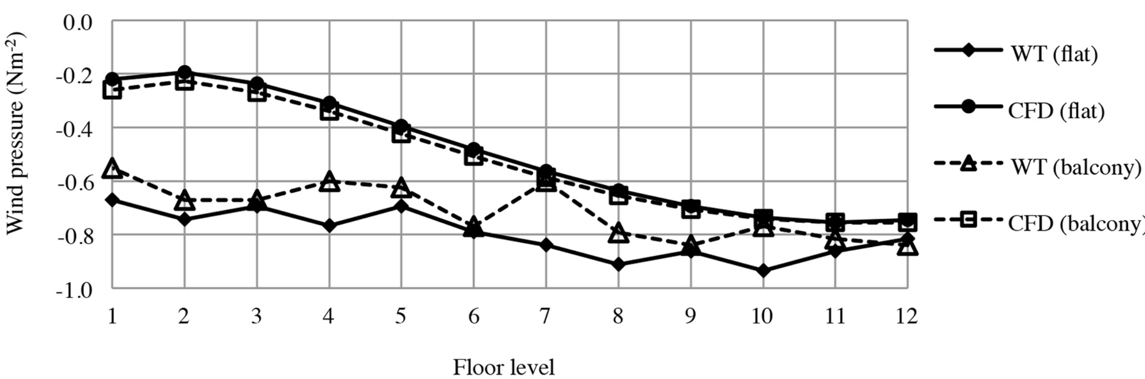


TABLE 2. Windward average wind pressure using wind tunnel experiment (WT) and CFX along Line A to C (windward facade) with a wind angle of 0°.

	Average wind pressure (Nm^{-2})					
	WT			CFD (with % of difference)		
	A	B	C	A	B	C
Flat	1.254	1.326	1.194	1.182 (5.7%)	1.396 (5.3%)	1.182 (1.0%)
Balcony	1.178	1.314	1.244	1.364 (15.8%)	1.400 (6.5%)	1.356 (9.0%)

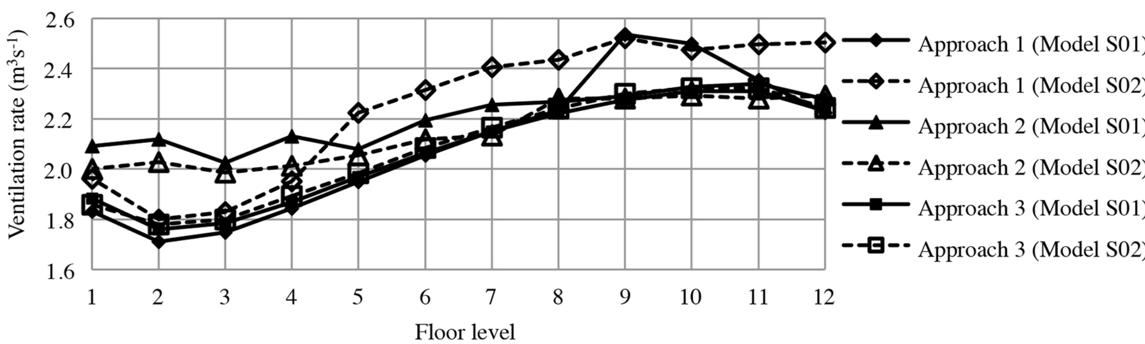
TABLE 3. Leeward average wind pressure using wind tunnel experiment (WT) and CFX along Line D to F (leeward facade) with a wind angle of 0°.

	Average wind pressure (Nm^{-2})					
	WT			CFD (with % of difference)		
	D	E	F	D	E	F
Flat	–0.861	–0.799	–0.911	–0.542 (37.0%)	–0.497 (37.8%)	–0.538 (40.9%)
Balcony	–0.822	–0.712	–0.814	–0.546 (33.6%)	–0.519 (27.1%)	–0.542 (33.4%)

TABLE 4. Ventilation rate predictions using Approaches 1 to 3 for the models (middle units only) with and without balconies with a wind angle of 0°.

	Average ventilation rate (m^3s^{-1})		
	Approach 1	Approach 2	Approach 3
Flat	2.095	2.200	2.069
Balcony	2.243	2.147	2.083

FIGURE 7. Comparison of ventilation rate predictions using the three approaches with a wind angle of 0°.

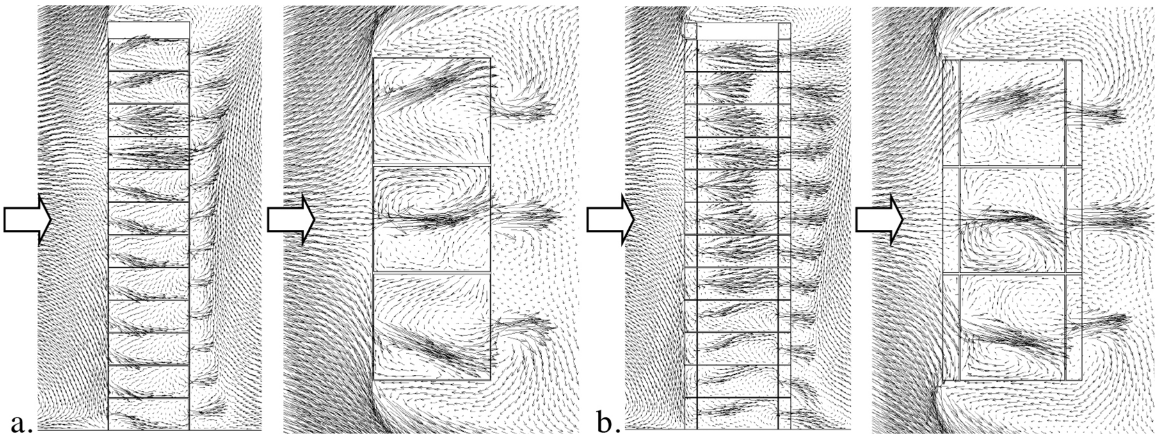


In the validation of the coupled CFD simulation (Approach 1), Table 4 suggests that the prediction by Approach 1 is the closest to Approach 2, thus the prediction by Approach 1 is acceptable. Although the average predicted ventilation rate by Approach 1 is the closest to Approach 2 (see Table 4), the ventilation rate predictions by Approach 1 show a distinct prediction difference from those by Approach 2 for almost all units (Fig. 7) could be due to the following reasons:

- An inaccurate value of the opening discharge coefficient, which varies because of the varying location of units and façade modifications. For example, introducing balconies that act as a wind scoop could improve the ventilation performance, and as outdoor airflow changes its direction downwards and parallel to the windward facade (see Fig. 8), the value of the opening discharge coefficient will be lower than units with a perpendicular wind.
- Limitations of the CFD prediction. For example, less accurate airflow prediction for airflow recirculation zones such as at the bottom of buildings due to the selected turbulence model (see discussion in Section 3.2).

This validation study suggests that Approach 1 is an appropriate and a reliable approach for the objective of this study that can predict ventilation performance and possible changes in ventilation performance due to facade modifications. This finding is further supported by Fig. 8, which shows the expected changes in indoor airflow characteristics due to the introduction of the balconies, where it is expected that the indoor airflows for bottom units with balconies are not influenced by the downward movement of wind flow pattern present in units with a flat facade because the balconies change the outdoor airflow characteristics near the opening surface.

FIGURE 8. Middle sections and plans (2.0 m above floor level at level 09) for Unit 3 showing airflow patterns for Model S01 (a) and Model S02 (b) with a wind angle of 0°. The large white arrows indicate the wind direction.



5. DISCUSSION ON THE EFFECTS OF BALCONY ON VENTILATION PERFROMANCE

The changes in ventilation performance as a result of facade modifications are discussed in the context of ventilation performance and indoor average airspeed. Fig. 9 to Fig. 14 compare the ventilation performance for Models S01 through S04 (all units along Line B only) under various wind directions (0°, 45° and 90°). Table 5 and Table 6 show the average ventilation rate and overall average indoor airspeed for Models S01 to S04.

5.1 Introduction of balconies

Fig. 8 shows the outdoor and indoor airflow patterns predicted by CFX using the coupled CFD simulation approach for Models S01 and S02 at a wind angle of 0°. The figure shows that CFD predicts changes in indoor airflow patterns resulting from the provision of balconies. The changes shown in the figure are as expected, where the flat facade (Model S01) indicates the direct influence of the overall outdoor airflow on indoor airflow patterns (Fig. 8a), whereas balconies in Model S02 act as an architectural element that changes the outdoor airflow characteristics close to the openings. Thus, the presence of balconies results in different

FIGURE 9. Ventilation rate for Models S01 to S04 at a wind angle of 0°.

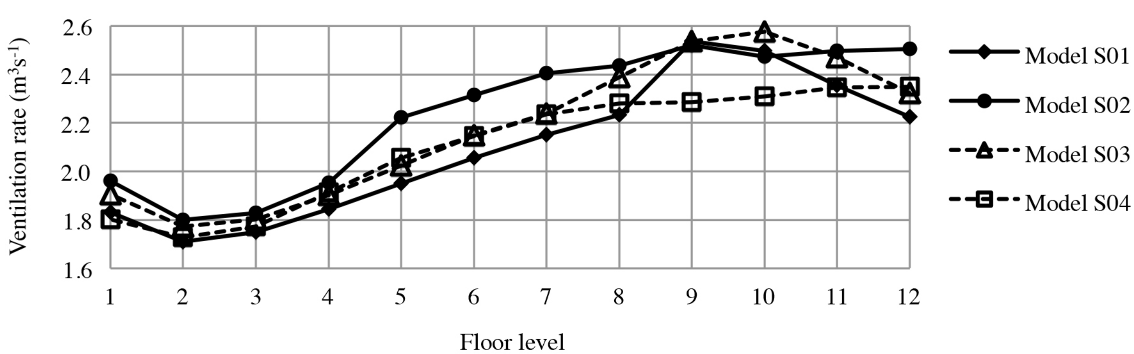


FIGURE 10. Average indoor air speed for Models S01 to S04 at a wind angle of 0°.

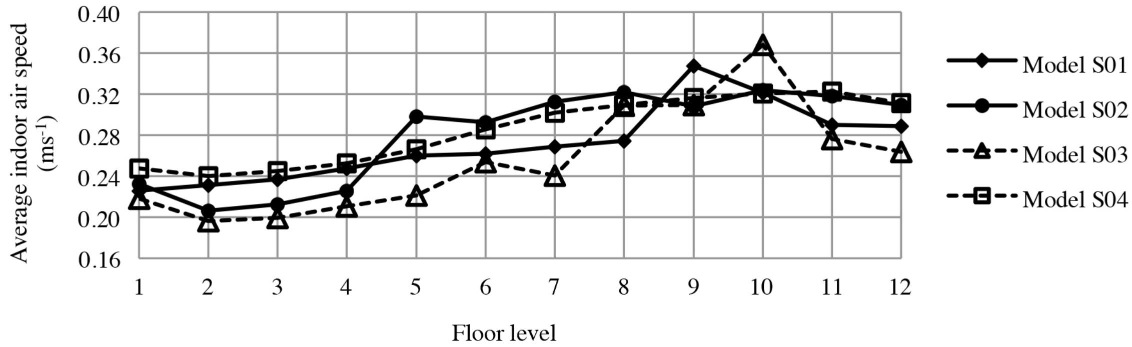


FIGURE 11. Ventilation rate for Models S01 to S04 at a wind angle of 45°.

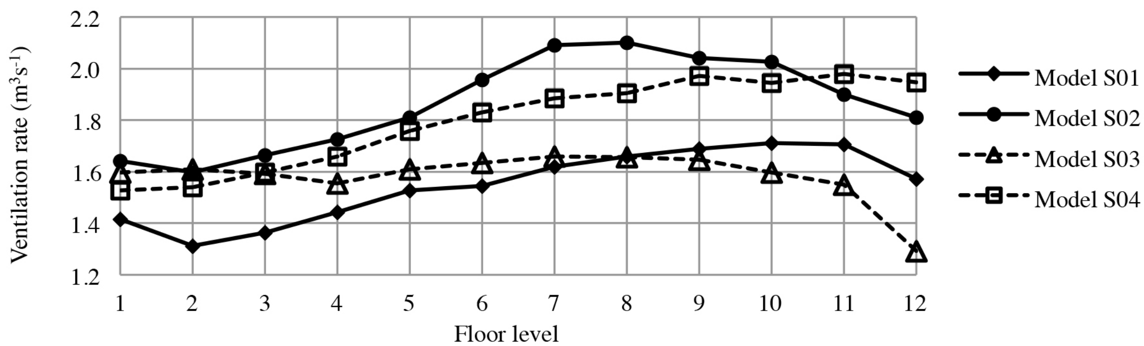


FIGURE 12. Average indoor air speed for Models S01 to S04 at a wind angle of 45°.

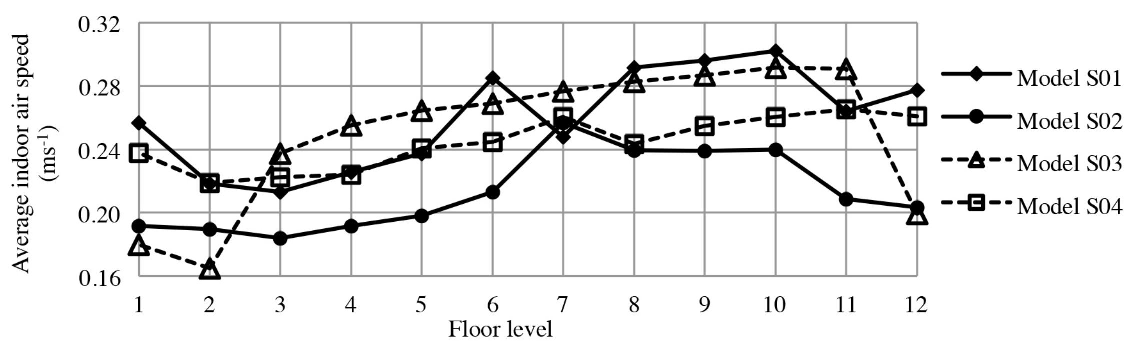


FIGURE 13. Ventilation rate for Models S01 to S04 at a wind angle of 90°.

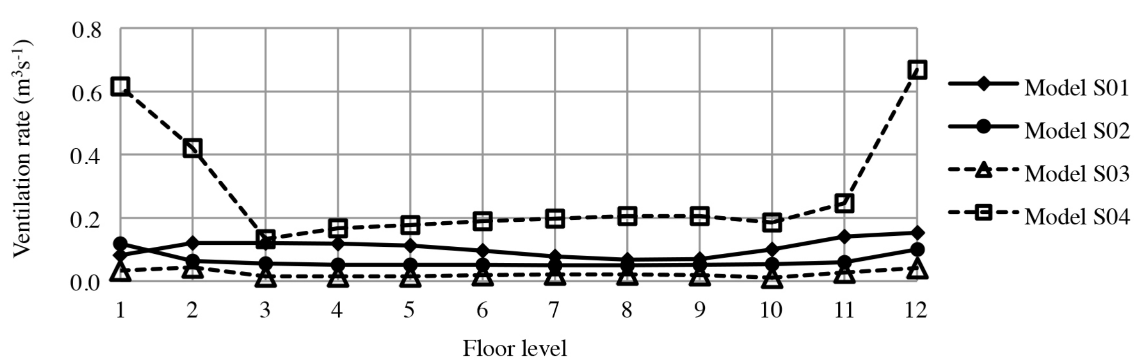


FIGURE 14. Average indoor air speed for Models S01 to S04 at a wind angle of 90°.

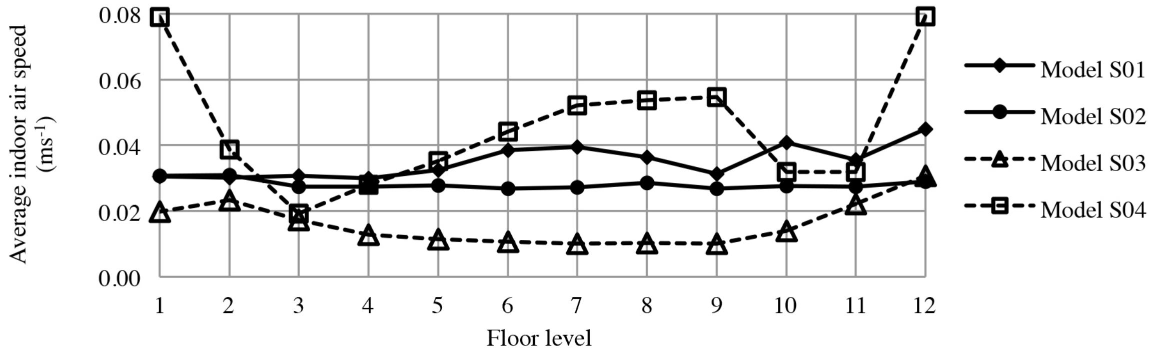


TABLE 5. The average ventilation rate for middle units along Line B.

Wind angle	Average ventilation rate (m^3s^{-1})			
	Model S01	Model S02	Model S03	Model S04
0°	2.095	2.243	2.174	2.102
45°	1.547	1.864	1.583	1.795
90°	0.105	0.063	0.024	0.285

TABLE 6. The overall average indoor air speed for middle units along Line B.

Wind angle	Overall average indoor air speed (ms^{-1})			
	Model S01	Model S02	Model S03	Model S04
0°	0.271	0.280	0.256	0.285
45°	0.260	0.213	0.250	0.245
90°	0.035	0.028	0.016	0.046

indoor airflow patterns compared with the flat façade: the balconies direct the airflow to the centre of the room toward the outlets (Fig. 8b). The changes are clearly shown in the sections and plans of the models in Fig. 8. These changes improve the ventilation rate of Model S02 by 7.1% compared with that of Model S01 (Table 5). However, for the overall average indoor airspeed, the improvement is only 1.3%.

For a wind angle of 45°, the introduction of balconies (Model S02) significantly improves the ventilation rate by 20.5% compared to that of Model S01. Although the ventilation rate improvement is significant, Table 6 shows that the overall average indoor air speed is reduced by 18.1%, which is also significant. This drop in wind speed results from the introduction of the balconies, which changes the indoor airflow pattern, thus reduces the average indoor air speed. Therefore, it can be concluded that, in this case, introducing balconies leads to poorer air distribution throughout the units compared with the air distribution in Model S01.

For a wind angle of 90°, it can be observed that the introduction of balconies (Model S02) reduces the ventilation rate and average indoor air speed of the building in all units (see Figure 13 and Fig. 14). Table 5 and Table 6 show the reductions in the ventilation rate and indoor air speed are 40.0% and 20.0%, respectively, compared with those of Model S01. This finding suggests that the introduction of the balconies leads to poorer ventilation performance at a wind angle of 90°, where the balconies act as a buffer space protecting the indoor space from the direct influence of the outdoor airflow.

5.2 The depth of balconies

The earlier discussion suggests that the introduction of balconies could influence the ventilation performance of cross ventilated buildings, either positively or negatively. In this study, two balcony depths are investigated: 1.5 m (Model S02) and 3.0 m (Model S03). Generally, it can be observed that the deeper balcony leads to poorer ventilation rates (Table 5) for all wind angles with reductions of 3.1%, 15.1% and 61.9% at 0°, 45° and 90°, respectively. In the case of average indoor airspeed (Table 6), reductions only occur at 0° and 90° at 8.6% and 42.9%, respectively. At 45°, although the reduction of ventilation rate is more than 15%, the increased balcony depth leads to an improved average indoor air speed of 17.4%. Generally, it can be concluded that an excessively deep balcony should be avoided because it could negatively affect the ventilation performance where the space within a deep balcony could act as a barrier to outdoor air penetration.

5.3 Modification of opening

A simple modification of the opening location (Model S04) is made in Model S02 to investigate how the modification influences ventilation performance. Figures 9 to 12, Tables 5 and Table 6, suggest that the modification result in a significant improvement of ventilation performance for a wind angle of 90°. Table 5 indicates that the improvement of ventilation rate for Model S04 against Model S02 is 352.4% at a wind angle 90°, which is significant. At 0° and 45°, even though there are reductions in the ventilation rate, the reduction is insignificant (6.3% and 3.7%) compared with the improvement at a wind angle of 90°. These findings indicate that a balcony could act as a better wind scoop if an opening is located close to a protrusion element.

In the case of average indoor airspeed, Table 6 shows that Model S04 performs better than Model S02 at all wind angles. The improvements are 1.8%, 19.2% and 64.8% at 0°, 45°, and 90° respectively.

5.4 Ventilation rate and indoor air speed

Another finding in this study is some contradiction between ventilation rate and average indoor air speed in describing the ventilation performance of the models investigated. The figures and tables shown in this section indicate that when considering an appropriate design solution to ensure good ventilation performance, considering the ventilation rate alone is insufficient. Parameters such as the average indoor airspeed are also important because it could better describe overall ventilation performance throughout a room than ventilation rate.

One of the reasons for the dissimilar performances of ventilation rate and indoor air speed is the presence of balconies with two oppositely arranged openings on windward and leeward walls, which could redirect the outdoor air to travel a shorter distance between the inlet and outlet that can be observed between Models S01 and S02. This phenomenon can be observed in Fig. 8, which shows that introducing balconies leads to air movement concentrating in the middle of the indoor space and moving towards the outlet opening, which results in a shorter air travel distance.

For the ventilation performance for all units along Line B, it can be observed that the trend for the ventilation rate is more predictable than the average indoor airspeed where areas with higher windward wind pressure values have higher ventilation rates. When the wind angle is 0°, it is known that units located within the pressure stagnation zone have greater wind pressure; thus, it can easily be predicted that the ventilation rates for these units are higher than those of other units.

6.0 CONCLUSIONS

In this study, the coupled CFD simulation (Approach 1) has been validated using various ventilation prediction approaches. The coupled CFD simulation has been used to investigate the ventilation performance for cross-ventilated high-rise buildings with various facade treatments. The following conclusions have been obtained:

- The coupled CFD simulation (Approach 1) is a reliable approach to investigate the changes in ventilation performance as a result of facade modifications. Approach 1 is also found to be superior to the approaches that apply empirical models; in this case, the pressure difference method due to comprehensive information provided and ability to predict airflow changes due to the introduction of the balconies. Additional to this, it is important to note the limitation of the turbulence model used in this study; for example, the less accurate wind pressure predictions on the leeward side.
- It can be observed that the ventilation performance for the cross ventilation strategy is at its best with a wind angle of 0°, and the worst ventilation performance occurs at a wind angle of 90°. Thus, it is important to design a layout of the cross-ventilated building to have a perpendicular prevailing wind direction.
- Although the introduction of balconies could lead to an enhanced or reduced ventilation rate, it does not necessarily provide a similar improvement or reduction in the context of indoor air speed.
- The relationship between balcony design and opening locations is important to ensure that the cross ventilation strategy is optimised. For example, placing an opening next to the wing wall element of a balcony could improve the effectiveness of the balcony as a wind scoop.
- The depth of the balcony also influences the effectiveness of the balcony as a wind scoop. A deep balcony (in this study, 3.0 m) leads to reduced ventilation performance compared with that of a shallower balcony (1.5 m). Balcony depth is especially critical at a wind angle of 90° because the space within the balcony could act as a buffer that prevents outdoor air from penetrating the indoor space.
- The ventilation rate performance for all vertically arranged units is more predictable than the average indoor airspeed. For example, the ventilation rate performance of vertically arranged units can be easily predicted based on windward wind pressure distribution.

The results obtained in this study are limited to a single opening dimension with three simple balcony designs. Thus, further research is necessary to have a better understanding of the effects of the opening configuration and balcony design on the ventilation performance of a cross-ventilated high-rise building. Further research is also needed to determine the relationship between ventilation performance and improved indoor air quality and thermal comfort.

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