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COMPUTATIONAL ANALYSIS ON THE EFFECTS OF FAÇADE MODIFICATIONS ON WIND-DRIVEN NATURAL VENTILATION PERFORMANCE OF A SINGLE-CELL ROOM

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ABSTRACT

Single-sided ventilated (SSV) buildings have been always assumed to be less efficient in natural ventilation performance compared to cross ventilated building, thus when a good ventilation performance is required in a building the single-sided ventilation strategy has always been ignored as an alternative ventilation strategy to cross ventilation. It is known that the cross ventilation strategy can generally perform better than the single sided ventilation. However, this is not necessarily true in all cases, due to various factors such as wind direction and façade treatment. The objective of this study is to investigate wind-driven natural ventilation performances for a single-cell room with various façade treatment options. This study explores various façade treatments, and the performance of each façade treatment is evaluated. This study uses computational analysis to investigate the ventilation performances. This research methodology is used due to its flexibility and post-processing advantage. This study found that façade treatments such as wing-wall and balcony can significantly influences the natural ventilation performance of a single-cell room.

Keywords: ventilation, computational fluid dynamics, and façade.

INTRODUCTION

Generally, cross ventilation has better performance than single-sided ventilation. Despite less effective ventilation strategy compared to cross ventilation, single-sided ventilation is commonly found in buildings due to various reasons such as land and cost constraints, space efficiency, privacy as well as building by-law requirements. Since cross-ventilation strategy is a preferred ventilation strategy in buildings, there are more available data on its performance than single-sided ventilation strategy. Therefore, lack of understanding on single-sided ventilation strategy could risk providing poor indoor air quality, especially if a designer only concerns on providing opening as required by law rather than focusing on whether adequate ventilation is provided. Thus, it is important to understand single-sided ventilation in order to ensure that the ventilation impact is optimized and the occupants of buildings are provided with good thermal comfort and healthy indoor air quality (IAQ). This includes understanding the performance of single-sided ventilation under different façade treatments and wind conditions. Thus, the objective of this study is to investigate wind-driven natural ventilation performance for a single-cell room with various façade treatments with the main focus is on single-sided ventilation strategy.

FAÇADE TREATMENTS

Openings, typically window and door, are the mediums for exchange between internal and external air if mechanical ventilation is not provided. Natural ventilation achievable by a room is dependent upon various factors, such as opening configurations, wind direction and building form. Opening configuration includes location, number, size and details of the opening. Façade reliefs other than opening also have a great influence on the air flow inside and outside buildings. Various façade reliefs, such as wing wall, louver, overhang and balcony, have been used for various purposes in building design, including in vernacular architecture [1-6]. Façade reliefs can improve ventilation performance of a room, for example; the incorporation of wing walls in single-sided ventilated (SSV) rooms improves indoor air flow [1, 5, 7, 8] compared to a room with similar opening size but with a flat façade.

For a SSV room, it limits opening or openings to be provided at a single façade. Since ventilation performance depends upon the pressure difference across an opening or between openings, the introduction of complex façade relief may change the pressure distribution on the façade, and this can be potentially utilized to improve indoor ventilation performance. Therefore, a complex façade treatment is seen as an opportunity to induce indoor airflow. However, it is also important to understand that a complex façade treatment is also a potential barrier to the outdoor air, thus reducing the ventilation performance.

METHODOLOGY

Model configurations

In this study, a set of façade designs is selected to investigate the effects of façade treatments on a SSV single-cell room. The dimension of the building configurations are based on the work by Givoni [9]. Model G01 to G04 (Figure-1) are the models that resemble the models tested by Givoni. Givoni’s work involves an investigation of an external protrusion which is similar to this study, thus it can be appropriately used as a reference for this study.

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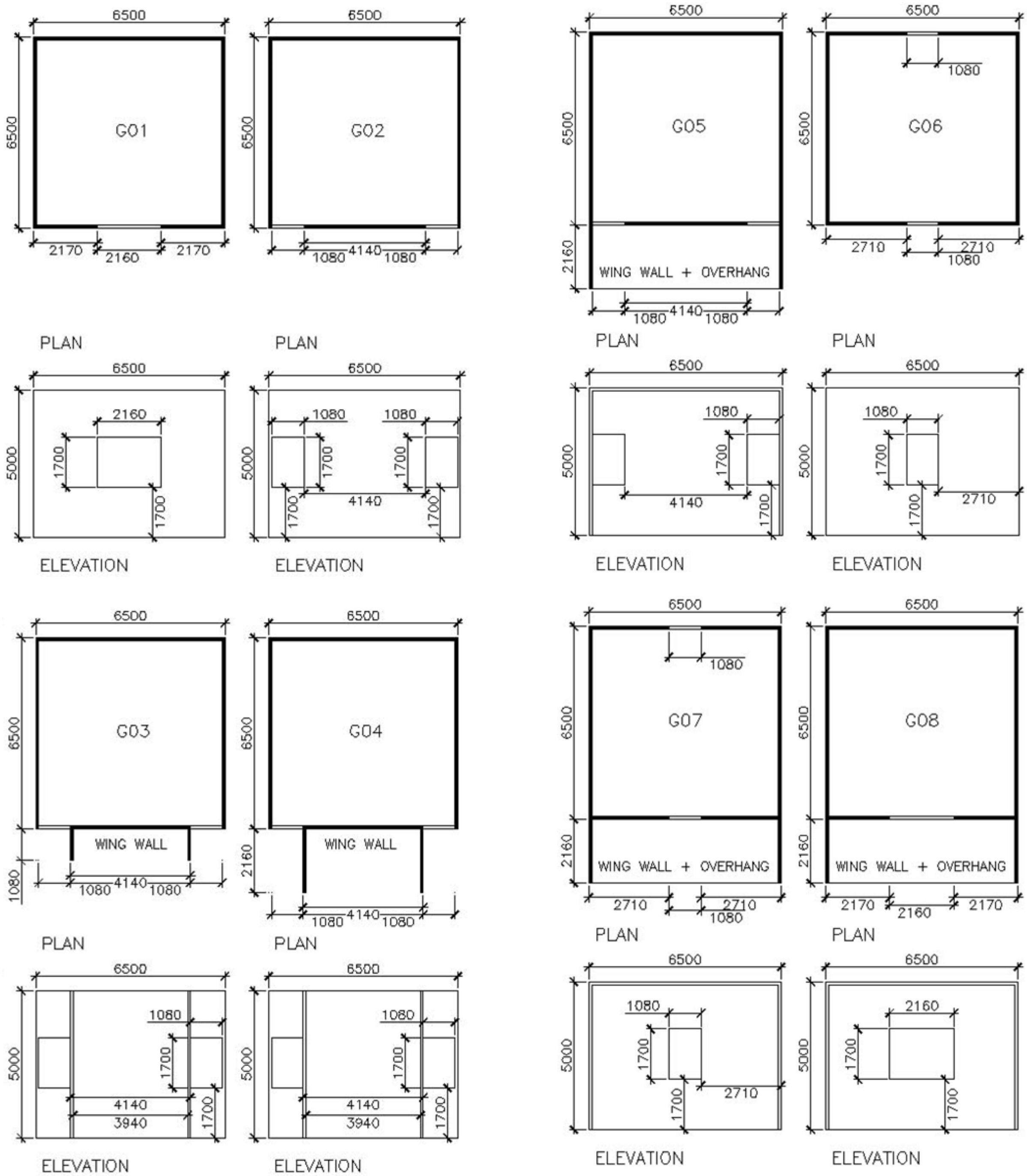

Figure-1. Building configurations (in milimetres) for case G01 to case G4 with each has a similar total opening area (3.672m2).

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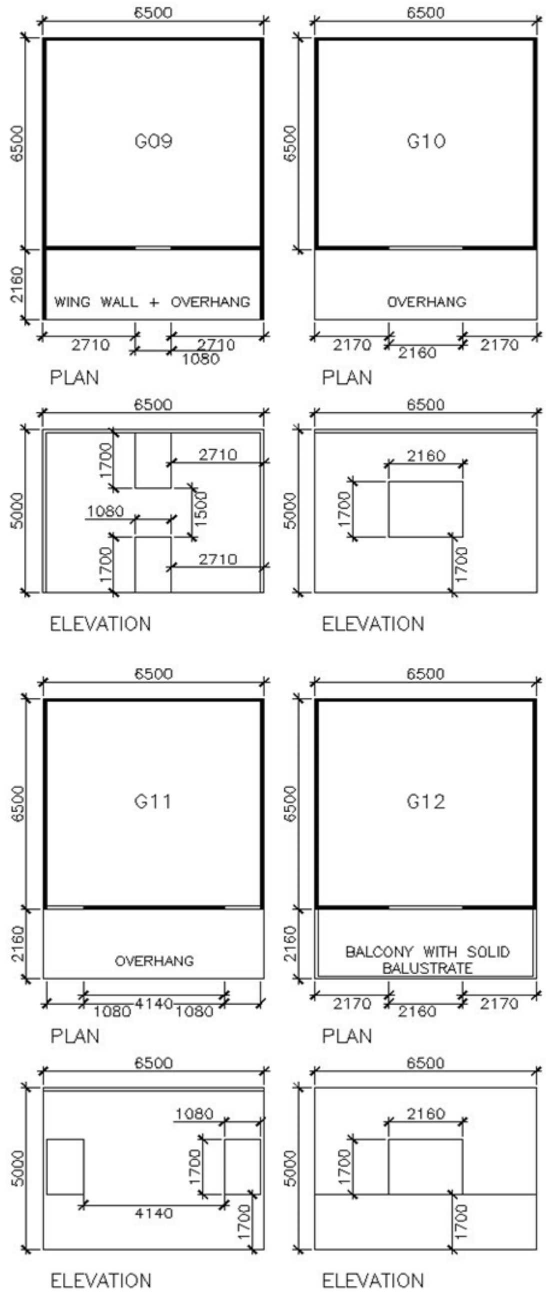

Figure-2. Building configurations (in milimetres) for Case G05 to Case G12.

Sixteen (16) room configurations (Figure-1-3) are analyzed with four of them are cross-ventilated room (Case G06, G07, G15 and G16). Two opening configurations are adopted in this study; they are single opening and double openings (two arrangements). The total opening area for each of the room configurations is similar (3.672 m2) except four (Case G13 to G16) which are used for validation study. Other than opening configuration, various protrusion elements are investigated: wing-wall, balcony with only horizontal protrusion, and balcony with both horizontal and vertical protrusions.

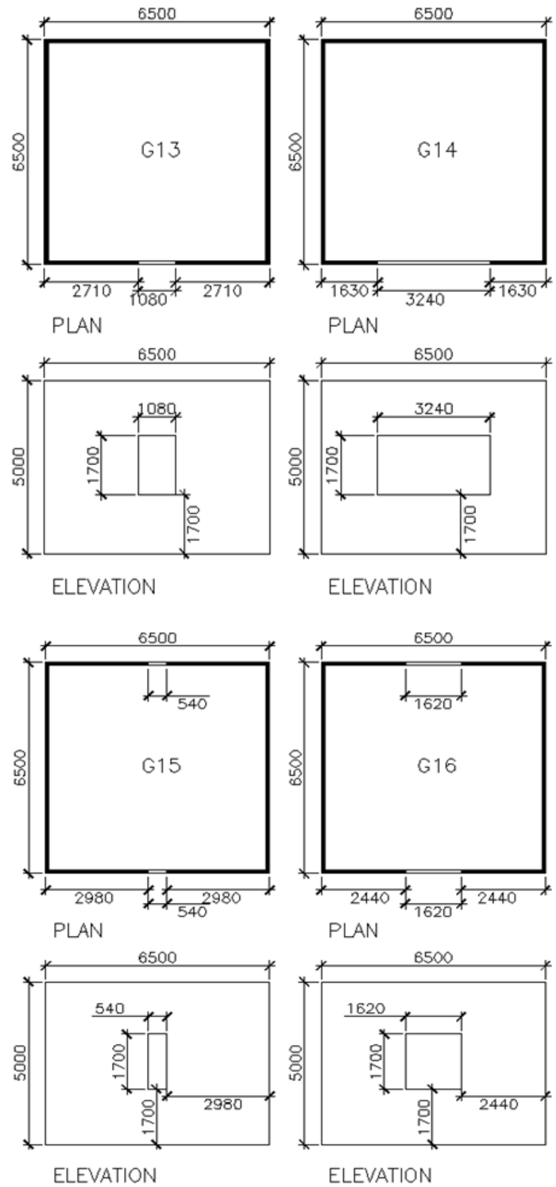

Figure-3. Building configurations (in milimetres) for PS1with total opening area of 1.836m2 (Model G13 and G15) and 7.344m2 (Model G14 and G16).

Prediction models

There are various airflow prediction models that predict the ventilation performance of buildings. Four of the commonly known airflow prediction models are: full-scale, small-scale, CFD and empirical models. Each of these models has their own advantages and disadvantages that make them relevant particular building's configurations [10, 11].

According to Chen[10] Computational Fluid Dynamics (CFD) is the most popular method for predicting ventilation performance in buildings. The CFD application is expected to expand and will become an important prediction model. The popularity of the CFD method is because it's many benefits: cost efficient, flexible, accurate prediction and provides comprehensive data. With these advantages, CFD application is selected the main prediction model in this study.

While the earlier discussion indicates that CFD has many advantages that make it appropriate for this study, it is important to note that CFD has two major limitations that need to be addressed: high computational effort and difficulties to assess CFD results. While the computational requirements of CFD can be addressed with more powerful computers and parallel processing, the later requires a greater attention where it requires a validation process.

In the case of a simple flat façade single-cell room, empirical models alone are generally adequate for predicting the indoor ventilation performance for both single-sided and cross ventilation strategies. Therefore, two approaches are used in this study which are: Fully empirical models (Approach A), and fully CFD models (Approach B). Fully CFD models (Approach B) means the ventilation prediction is obtained from CFD simulation, while Approach a means prediction is obtained from equations. Approach B is the main approach applied to investigate all models, while Approach A is used for validation of Approach B. Three equations are used in Approach A, Equation 1, Equation 2 and Equation 3, as below, which are obtained from Warren and Parkins [12], De Gibs and Phaff [13] and Larsen [14], respectively

$$Q = C_v A V \tag{1}$$

$$Q = 0.5A\sqrt{0.001.(V)^2 + 0.001} \tag{2}$$

$$Q = A\sqrt{C_n.|C_p|.V^2} \tag{3}$$

Q = Ventilation rate (m^3s^{-1})
C_v = Opening effectiveness (dimensionless)
A = Opening area (m^2)
V = Wind speed (ms^{-1})
C_p = Pressure coefficient (dimensionless)
C_n = Constant (windward/ parallel wind: 0.0012 and leeward wind: 0.0026) (dimensionless)

Among all the equation, Equation 1 is the simplest and the most common equation for single-cell room that can be applied for both single-sided and cross ventilated rooms. For Equation 1 (cross ventilation only), the C_v values used for validation are between 0.5 and 0.7 for perpendicular wind[15]. In the case of diagonal wind, range between 0.25 to 0.48 are used as suggested by Ashrae [15] between 0.25 to 0.35; and as a study by Larsen[14] which is 0.48. In the case of single-sided ventilation, the C_v value used in Equation 1 is 0.025 [12]. For Equation 2[13] and Equation 3 [14], the equations are limited to single-sided ventilation only. In Equation 3, the C_p values used are taken from Liddament[16].

Validation study

It is important to note that this study only focuses on wind-driven ventilation. Thus, the effect of thermal-driven ventilation is not considered, where the temperature within and outside the buildings are assumed to be in adiabatic condition. The tested wind speed for ventilation performance comparison is limited to a single speed (3 ms-1) in which the wind speed is equally distributed throughout the inlet to resemble the wind tunnel experiment set up by Larsen [14] and Givoni [9]. The wind angle is limited to 0º, 45º and 135º. In validation study, six models are compared: Model G01, G06, G13, G14, G15 and G16. Model G01 and G06 are the reference models, while other models are developed from these models which have smaller or larger opening area. The validation study is only limited for flat façade models.

Other than opening size, another parameter tested is wind direction. Two wind directions are tested: 0º (all the six models) and 45º (Model G01 and G06 only). For 45º wind angle, the model is rotated clockwise. It is important to note that for single-sided ventilation with opening on the leeward side is excluded due to two factors: CFD prediction for leeward side is inaccurate as shown in other studies such as by Montazeri *et al.* [17], Mohamed *et al.* [11], Yim *et al.*[18], Yang[19] and Yoshie *et al.* [20]; and, there is no appropriate empirical model that acceptably accurate to predict ventilation performance for single-sided ventilation with opening on the leeward side. With variables of opening configuration and wind angle, a total of eight cases is tested in validation study as shown in Table-1. Each CFD prediction on the models is then validated with the predictions using empirical models (Approach A).

Table-1. List of all cases for validation study.

Case	Model	Wind Angle
1	G01	0 º
2	G13	0 º
3	G14	0 º
4	G01	45 º
5	G06	0 º
6	G15	0 º
7	G16	0 º
8	G06	45 º

COMPUTATIONAL FLUID DYNAMICS (CFD)

CFD Setup

CFD commercial software known as Ansys CFX 12.0 is used in this study with the standard k-epsilon model. The turbulence model is selected because its robustness and has a reasonable computational effort. The

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turbulence model also has been applied by other researchers to simultaneously simulate outdoor and indoor airflows such as by Cheung and Liu[21]. This study adopts a steady-state CFD simulation under an isothermal condition. The CFD domain and CFD Meshing are shown in Figure-4 and Figure-5, respectively.

Table-2. Final mesh setup for the simultaneous simulation of outdoor and indoor airflows.

Element size on façades (Incl. indoor**)**	**Element size on building's edge (**incl. indoor**)**	**Element size at opening (**m**)**	**Expansion ratio (**growth rate**)**
0.3	0.2	0.05 (17x28)	1.2*

* Except on surfaces and edges of opening, building and ground which use 1.0 expansion ratio.

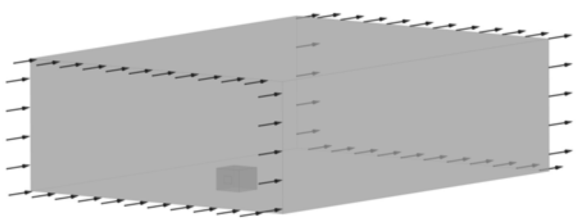

Figure-4. CFD domain for Model G01 at 0° wind angle.

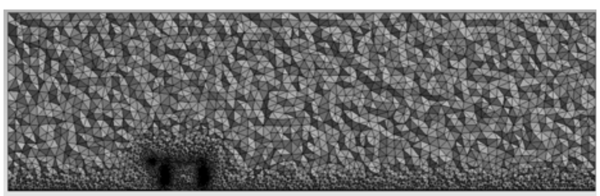

Figure-5. CFD meshing for model G07.

Validation Results

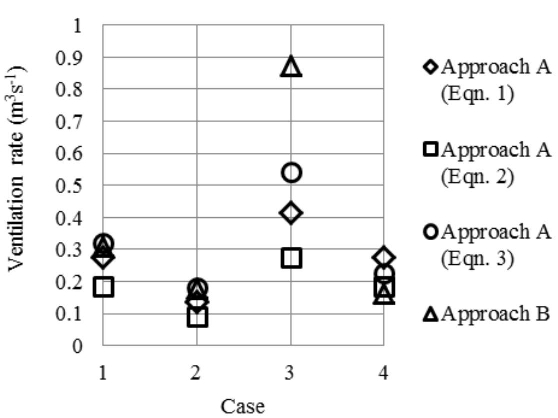

Figure-6. CFD prediction of ventilation rate for case 1 to case 4.

For Case 4, Approach B shows good agreement with Approach A (Equation. 2) while it under-predicts in comparison to the others. While Approach A with Equation 1 and Equation 2 do not include the effect of two different wind angles (0º and 45º), Approach A with Equation. 3 suggests reduction of wind performance for 45º in comparison to 0º. Similarly, Approach B has also captured the reduction of ventilation performance in 45º wind angle. This suggests that Approach B has shown acceptable ventilation prediction, though the value is arguable due to inadequate validation.

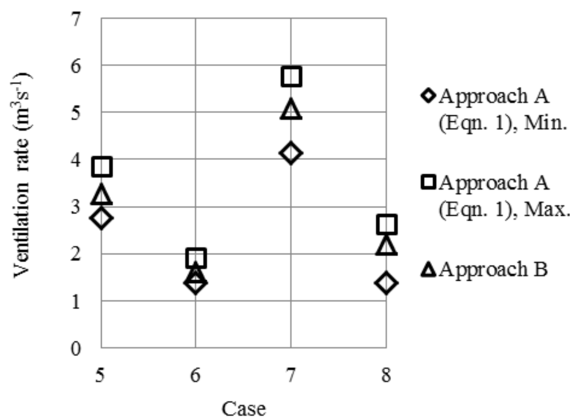

Figure-7. CFD prediction of ventilation rate for case 5 to case 8.

Figure-7 shows the predictions of ventilation rate for the cross ventilated models (Model 05 to Model 08). The figure shows that Approach B can predict ventilation rates within the prediction ranges of Approach A for both wind angles. This finding suggests that Approach A can acceptably predicts ventilation rate for cross ventilation strategy. Even though, there is an over prediction for Case 3 (single-sided ventilation strategy), the ventilation prediction by Approach B still acceptable for this study since the ratio of opening size to façade area is large(17%) and the applied equations for validation is derived from a much smaller ratio than this.

FINDINGS

Figure-8 and Figure-9 show the CFD predictions for the twelve models with a similar total opening area but with various façade treatments under 0º and 45º wind angles, respectively. The figures have shown that the ventilation strategy and façade treatment play a very important role in determining the ventilation performance in buildings.

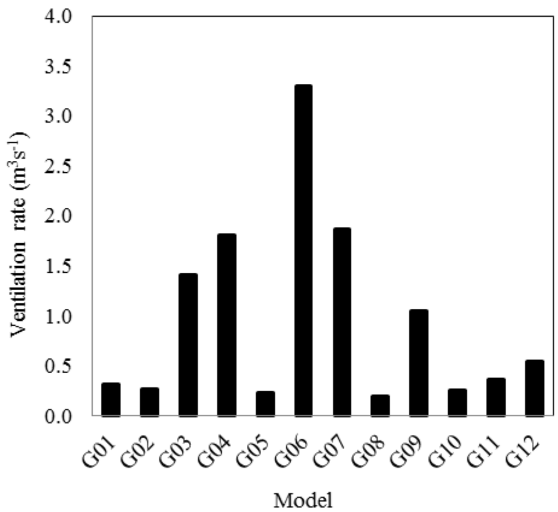

Figure-8. CFD prediction of ventilation rate for model G01 to G12 at wind directions of 0°.

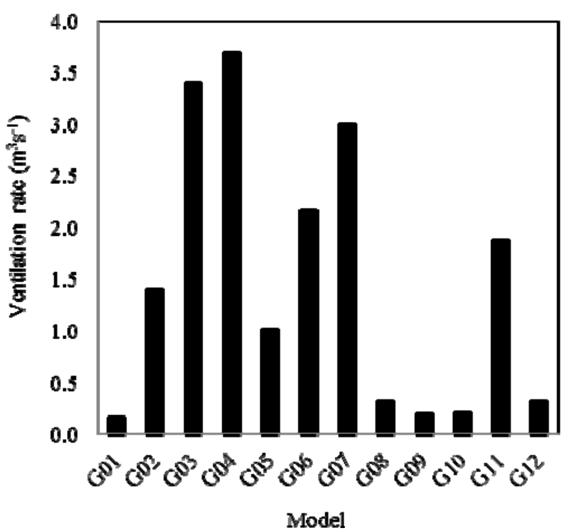

Figure-9. CFD prediction of ventilation rate for model G01 to G12 at wind directions of 45°.

Effects of balcony on cross ventilated room

The provision of a full-width balcony in a cross ventilated room is found to change the ventilation performance of a room. The provision of full-width balcony (Model G07) results in a reduction of ventilation performance in comparison to flat façade model (Model G06) at 0° wind angle with reduction by 44%. However, at 45°, the balcony improves ventilation performance by 38%. The reduction at 0° is due to the space within the balcony acts as a buffer where the air circulating within the balcony, thus preventing direct penetration of outdoor air. In the case of 45° wind angle, the balcony affectively scoops outdoor air into the indoor space, and reduces the effect of the wind curtain where, in Model G06, the outdoor air flows almost parallel to the building façade and the surface of the opening.

Effects of balcony on single-sided ventilated room

For single-sided ventilation, similar to cross the ventilated room, the introduction of the full-width balcony could lead to either improved or diminished ventilation performance. For a SSV room with flat façade and a single opening (Model G01), the provision of a balcony (Model G08) enhances the ventilation performance at 45° with improvement by 99%, while at the other wind angle (0°) the ventilation performance is reduced by 39%.

However, for horizontally arranged double openings with flat façade (Model G02), the provision of the full-width balcony (Model G05) is found to slightly reduce ventilation performance at both 0° and 45°, with reductions of 11% and 28%, respectively.

In the case of the vertically arranged openings (Model G09), it is found that the ventilation performance is significantly reduced (by 85%) at 45° in comparison to Model G02. However, a significant improvement is obtained at 0°, in which it is increased by 299%. The reason for the significant improvement at 0º is the upwards air movement due to the incident on the windward wall is scooped into the indoor space by the upper horizontal protrusion through the upper opening.

For the balcony with only horizontal protrusion, as in Model G10 and G11, the introduction of the protruding element does not significantly change the ventilation performance except for Model G11 at 45º wind angle in comparison to Model G02. The improvement is found to be of 33% higher than Model G02. It is also found that the model also has better performance than Model G05, the model with horizontal and vertical protrusions. However, for the single opening at 45º wind angle, contradicting finding is found where the model with horizontal and vertical protrusions (Model G08) performs better than the model with only horizontal protrusion (Model G10). This finding further suggests that the protrusion could help to improve the ventilation performance; however, it requires careful application since if inappropriately applied, the ventilation performance could be reduced.

Effects of wing-wall on single-sided ventilated room

Figure-8 shows that the models with wing-wall (Model G03 and G04) have the best ventilation performance among all the single-sided ventilated room. At 0º wind angle, cross ventilation strategy has shown better ventilation performance than the single-sided ventilated models noting that Model G07 has almost similar ventilation performance in comparison to Model G04. In the case of 45º wind angle, Figure-8 shows that the models with wing-wall perform better than other models, including those with cross ventilation strategy (Model G06 and G07).

It also can be observed that at 0º, the ventilate rate for Model G04 is 6 times Model G01. At 45º, the ventilation rate for Model G04 (the highest) is 22 times better than Model G01 (the lowest). In this case, with diagonal wind angle, the protruding elements of the wing-wall create a positive and negative areas at two openings, and at the same time the front protruding element becomes an effective element to scoop the incoming air into the indoor space. This finding shows that façade modification and wind angle play an important role in determining the ventilation performance of a room.

Effects of opening configuration

The results shown in Figure-8 and Figure-9 also demonstrate that opening configuration is another factor that critically influences the ventilation performance of a single-cell room. It is obvious that locating two openings on two opposite walls (cross ventilation) would be a better option than providing opening only on a single wall (single-sided ventilation), though in special cases, the performance of single-sided ventilation strategy could be better such as in the case of Model G03 and Model G04 at 45º wind angle. Thus, in the case of cross ventilation is not possible to be adopted in a building design, an appropriately designed façade treatment could improve the performance of single-sided ventilation strategy where, in certain conditions, it could perform better cross ventilation strategy.

In the case of single-sided ventilation, the provision of double openings in a SSV room, generally, can improve ventilation performance over that of a single opening of similar total opening area. This can be observed in most of the models at 45º, except Model G09. In the case of 0º, there is no significant difference can be observed for flat façade and full-width balcony; however, the introduction of an inner wing wall (Model G03 and Model G04) or vertically arranged double openings with horizontal and vertical protrusions (Model G09) improves the ventilation performance of the SSV room.

Comparison between single-sided and cross ventilated room

It can be clearly observed in Figure-7 and Figure-8 that cross ventilation strategy (Model G06 and G07) is the best strategy, performing well at both wind angles. However, at 45°, single-sided ventilation can perform better than the CV models if an appropriate façade relief is adopted. This can be observed in Model G03 and Model G04, where the performances surpass those of Model G06 and Model G07. Therefore, it can be concluded that cross ventilation strategy is a better ventilation strategy solution, but it is important to understand that the strategy not always performs better than single-sided ventilation where with an appropriate façade treatment, single-sided ventilation strategy can be optimized and performs better.

CONCLUSIONS

Generally, it can be concluded that even though only two types of opening configuration are used; a wide range of ventilation performance can be achieved. In the case of SSV models, its performances are greatly varied, which are due to the effects of the provision of external protrusions and wind direction. In some instances, the performance of SSV models can surpass the performance of models with cross ventilation strategy. This study also suggests that the ventilation performance of SSV room can be significantly improved with the introduction of wing walls (inner protrusions) such as in Model G04; however, the introduction of inappropriate configurations of protrusion could result in a significantly reduced ventilation performance, such as in Model G08.

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