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Investigation of the effect of balconies on natural ventilation of dwellings in high-rise residential buildings in subtropical climate

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Abstract: Balconies, as one of the main architectural features in subtropical climates, are assumed to enhance the ventilation performance of buildings by redirecting the wind. Although there are some studies on the effect of balconies on natural ventilation inside buildings, the majority have been conducted on single zone buildings with simple geometries. The purpose of this study is to explore the effect of balconies on the internal air flow pattern and ventilation performance of multi-storey residential buildings with internal partitions. To this end, a sample residential unit was selected for investigation and three different conditions tested, base case (no balcony), an open balcony and a semi-enclosed balcony. Computational Fluid Dynamics is used as an analysis method due to its accuracy and ability to provide detailed results. The cases are analysed in terms of average velocity, flow uniformity and number of Air Changes per Hour (ACH). The results suggest the introduction of a semi-enclosed balcony into high-rise dwellings improves the average velocity and flow uniformity. Integrating an open balcony results in reduction of the aforementioned parameters at 0° wind incidence.

Keywords: Natural Ventilation; Balcony; High-rise residential; CFD.

1. Introduction

Natural ventilation is considered as an effective passive strategy for cooling and reducing buildings' energy consumption especially in tropical and subtropical climates. As natural ventilation does not consume any fossil fuels, it can significantly reduce CO_2 emissions while maintaining good indoor air quality. Energy consumption in high-rise buildings can be accelerated with an inappropriate design and contribute to higher urban energy consumption in overall (Kennedy *et al.*, 2015). Hence, implementing passive strategies such as natural ventilation and daylighting for designing high-rise buildings could lead to significant energy savings. Furthermore, high-rise buildings are exposed to higher speed wind profiles due to their height and less obstructed surroundings. Thus, implementation of natural ventilation is more feasible.

While natural ventilation is a passive cooling strategy, relying on natural ventilation as a sole cooling strategy in climates with extreme weather conditions including high temperature and humidity for the most portion of a year could be quite unpractical. However, in mild climates such as Brisbane, where more than 60% of the year is within the comfort zone (temperature of 18 to 28℃) natural ventilation could be considered as an effective passive cooling system (Shah Nazari, 2014).

There are various influential parameters that have effect on natural ventilation in buildings. Some depend on the climate and the environment and cannot be controlled by architects such as wind speed, direction and temperature, while some can be addressed through an appropriate design. These parameters include building height and orientation, size and configuration of openings, internal obstacles and façade design. Researchers who explored these parameters and their influence on natural ventilation include (Mak *et al.*, 2007; Gao and Lee, 2011b; Fung and Lee, 2014).

One of the façade design features that can affect natural ventilation performance of buildings is balcony. Balconies are one of the main architectural features in subtropical climates (Buys *et al.*, 2008), being used as a private outdoor space, while potentially providing benefits to indoor air flows. There are some studies investigating the impact of the provision of balconies on indoor airflow in low-rise buildings. Prianto and Depcker (Prianto and Depecker, 2002) pointed out balconies have significant influence on indoor air movement and they will result in increase in internal air velocity. Chand et al. (Chand *et al.*, 1998) conducted an experiment to investigate the effect of balcony provision on pressure distribution on the building façade. They found wind pressure distribution alters on the windward side but not significantly on the leeward side and provision of balcony would result in increase in wind pressure in most cases they studied. Additionally, Ai et al. (Ai *et al.*, 2011b) used their experiment to research the impact of balconies on internal average velocity and mass flow rate. They concluded in single-sided ventilation, the addition of a balcony on the leeward side would lead to an increase in mass flow rate, while in cross ventilation no significant changes were observed for 0° and 45° wind incidences.

A good body of literature can be found around balconies and their effect on thermal comfort and energy performance in buildings (Prianto and Depecker, 2003; Chan and Chow, 2010; Ai *et al.*, 2011a). However little work has been done on examining the influence on introducing balconies to high-rise dwellings on natural ventilation in subtropical climates.

This study uses CFD to evaluate the influence of balconies on ventilation performance and flow distribution of an entire unit in a high-rise residential building in a subtropical climate. This method has been used in many similar studies (Jiang *et al.*, 2003; Gao and Lee, 2011b; Chu and Chiang, 2013; Fung and Lee, 2014). Grid sensitivity analysis was conducted to eliminate the errors associated with the grid size. A sample residential unit without a balcony is taken as the base case. The same unit layout, with an open and a semi-enclosed balcony were then explored and compared to the base case. This was to investigate the effect of different balcony types on internal airflow distribution and natural ventilation. Performance is analysed based on relative values of average air velocity, flow uniformity and the number of ACH.

2. Case Study

In order to conduct this study, a unit in a multi-storey dwelling design, which was constructed from a charrette (Kennedy and Thompson, 2011), was chosen as the case study. The main design intention for these case studies were to provide ample daylighting and natural ventilation by allocating proper length for daylighting (Garcia Hansen *et al.*, 2012) and providing cross ventilation in order to facilitate natural ventilation. The chosen apartment building consists of 17 floors, each floor contains four residential units, and it is designed for a site located in Brisbane, Australia. Figure 1 shows the original floor plan and an elevation of the selected unit for this study.

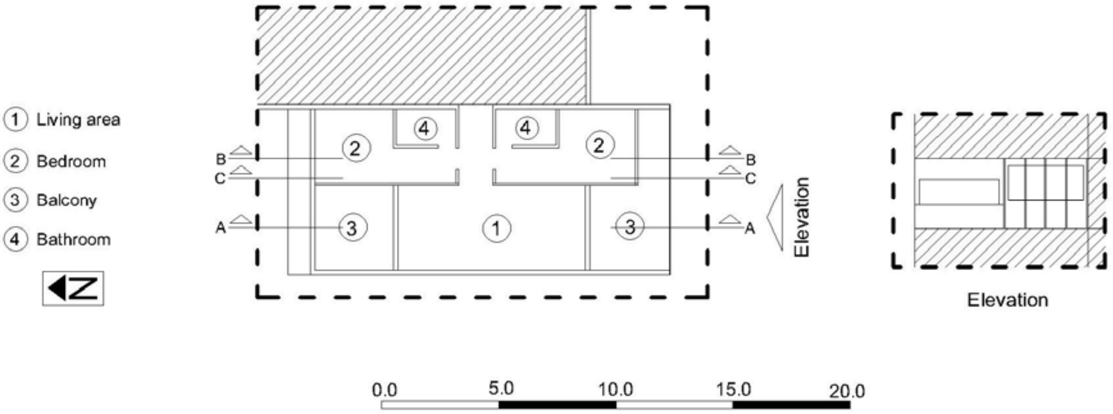

Figure 1: the original case study floor plan from charrette design.

Detailed explanation of the charrette designs can be found in (Omrani *et al.*, 2014). For the current study, the original floor plan was modified into a symmetrical plan layout in order to limit the variables. It contains two bedrooms, two bathrooms, a living area and two balconies at opposite sides that allow cross ventilation through the unit. The length of each balcony attached to the living room is three meters.

In order to assess the effect of balconies on natural ventilation, three case studies were used for this research: selected residential unit with open balconies, semi-enclosed balconies and without balconies. These three cases are explained below.

Case 1: the primary design without any balconies.

Case 2: the primary design with two balconies at two sides of living room. Eastern balcony wall is adjacent to the bedroom and the height of parapet wall at two other sides is one meter from floor.

Case 3: similar to Case 2, the only difference is height of balconies western walls which is from floor to ceiling (three meters).

3. Methodology

This study uses CFD to investigate flow behaviour in the three case studies. CFD is the most used method for evaluating air flow behaviour inside and outside the buildings due to the relatively low cost compared with experimental tests, its effectiveness as a design stage tool, and its accuracy (Chen, 2009).

Hence, several studies have implemented CFD as a method for natural ventilation evaluation in buildings (Jiang *et al.*, 2003; Gao and Lee, 2011b; Chu and Chiang, 2013; Fung and Lee, 2014).

In this study, the commercial CFD code FLUENT was employed for all simulations. Turbulence has been modelled with the two-equation RNG k-ϵ, which is one of the most common turbulence models for wind driven natural ventilation studies (Jiru and Bitsuamlak, 2010). The pressure-velocity coupling scheme was selected and spatial discretization parameters were set to second order upwind. The simulations were conducted in steady-state mode and gravity was activated.

Some simplifications and idealisations were applied to the simulations such as neglecting the furniture, modelling the apartment building as a bulk except for the unit of interest, neglecting the effect of surrounding buildings and assuming the openings are fully open. The assumptions were kept the same for all the three case studies. As the aim of this paper is to compare different balcony types to each other rather than obtaining absolute values, retaining the same conditions for all case studies limits the effect of idealised assumptions on outcomes.

3.1. Computational domain

A three dimensional full-scale model of the whole apartment within its computational domain was constructed using AutoCAD software. The domain size was based on a previous study by Gao and Lee (Gao and Lee, 2011a) with overall dimensions of 5Length x 5Width x 5Height of the building.

3.2. Mesh and grid sensitivity analysis

An unstructured quad dominant mesh was generated for this study using the ICEM CFD (*ICEM*, 2013) meshing software. A grid sensitivity analysis was conducted in order to obtain a grid independent solution. Three cases of coarse, medium and fine mesh consisting of about 1.5, 2.5 and 3.5 million elements respectively were generated. Grid density was increased near crucial parts such as unit of interest volume, walls and openings, in order to more accurately capture the fluid dynamic behaviour. The generated meshes were applied to the base case (without balcony) and results were compared in terms of average velocity through the entire unit. The average velocity differed by 6.4% from coarse to medium meshes and only 1.6% from medium to fine meshes. Due to excessive computational time required for the fine mesh, medium mesh was adopted for the three case studies.

3.3. Boundary condition

An inlet boundary layer profile was considered for an upwind boundary condition using the power law equation:

$$\frac{Vz}{Vref} = \left(\frac{Z}{Zref}\right)^{\alpha} \qquad (1)$$

Where V_z is the mean velocity (m.s^{-1}) at height Z (m), V_{ref} is the velocity (m.s^{-1}) at reference height and α is the power low exponent characteristic of terrain roughness. In this study V_{ref} is an average of Brisbane wind speed at 30°C temperature which was measured at reference height of 10m (Z_{ref}) extracted from Brisbane 30-minute weather data over 15 years collected by Australian bureau of meteorology. Furthermore, the α exponent was set to 0.25 based on Aynsley et al. (Aynsley et al., 1977) who suggest this value for suburban areas. Additionally, the wind angle was set to 0° (perpendicular to the openings) in order to study the air flow through the building at optimum orientation.

The same boundary conditions were set for all three cases. The outlet boundary condition was set to pressure outlet, top and side boundaries were set to symmetry and the ground boundary condition was defined as a wall.

4. Results and Discussion

The results from the CFD simulations are presented in terms of average velocity, flow uniformity and number of Air Changes per Hour (ACH) in three different cases. The number of ACH (h^{-1}) is calculated as below:

$$ACH = \frac{3600Q}{Vol} \tag{2}$$

Where Q ($m^3.s^{-1}$) is volumetric flow rate and Vol (m^3) is the total volume of the space.

The results of each case study were demonstrated in three layers at different heights of 0.6 m, 1.2 m and 1.8 m from the unit floor. These heights were selected as they are within the breathable zone and can be referred to human body sleeping, sitting and standing position height respectively. For each scenario, the air flow distribution is shown on three vertical sections, two sections through bedrooms and one in the living area (refer to Figure 1). The bathroom doors were assumed to be closed, therefore no air movement is evident in those zones. Figure 4 illustrates the air velocity magnitude and air flow distribution at the selected heights. Dark blue refers to zero velocity magnitude and the red colour illustrates the highest velocity magnitude (6.0 $m.s^{-1}$). Black vectors represent the flow direction at each point of the space. Although Case 1 does not have any balconies, the areas allocated to the balconies in other cases are also presented in Case 1 plans in order to allow the comparison of flow behaviour within these areas in all three cases. The wind direction

The following observations can be interpreted from Figures 3 and 4:

- The most uniform air flow distribution is through Case 3 and the least air flow uniformity is through Case 2, regardless of the height. This can be explained by the redirecting effect the western balcony wall has in Case 3.
- By looking at the Figure 3 graphs, the lowest average velocity can be seen in Case 2 at all three studied heights. The average velocity in Case 3 is higher than the average velocity in Case 1 near the ground (0.6 m) then it decreases and falls slightly below that of in Case 1 at the height of 1.2 m and eventually they reach equal values at the height of 1.8 m (1.5 $m.s^{-1}$).
- The lowest average velocity among the investigated heights can be observed at the height of 1.8 m for all cases. As the openings end at heights of 2.1 m and 2.7 m for living area and bedrooms respectively, this would cause minimal air flow movement at higher heights and recirculation zones above the openings.
- Given the dark blue as 0 $m.s^{-1}$ velocity magnitude, the first bedroom in all cases has minimal air movement at the height of 0.6 m where it is most required. It can be related to the height of bedroom opening, which starts from 1.2 m above the unit floor. Furthermore, a high-speed air flow region can be observed through the second bedroom which is not desirable. It can be the result of total air flow entered from bedroom one window, passing through bedroom two,

through a comparatively small opening. It may also be the influence of some portion of air from the living space passing through this area as well.

- In Case 2, there is a high speed air flow region on the windward side balcony at height of 1.8 m which cannot be seen in other cases. This could be because the balcony wall resists the air flow and directs the air through the gap between the ceiling and the balcony wall. Even though there is a similar gap in Case 3, the wall on the western side of the balcony prevents the high speed air flow on the balcony.

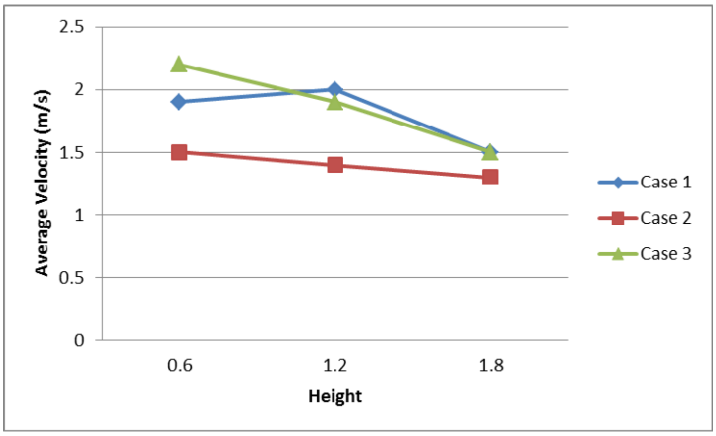

Figure 3: The average velocity at three heights (0.6 m, 1.2 m and 1.8 m) for the three case studies.

- Not having any obstacles in the balcony area in Case 1 results in a high speed air flow which travels almost diagonally through the balcony area. This leads to an inconsistent air flow in the living area i.e. a stream of air will travel at a high speed near the living area wall.

Figure 5 represents the velocity magnitude and air flow pattern on three sections through each case. One section passes through the middle of the living area (Section A-A), one from the bedroom doors (Section B-B) and the other close to the bedrooms western wall (Section C-C) - refer to Figure 1. The following observations can be drawn from figure 5:

- The obstruction that the balcony parapet wall makes on the windward side results in less uniform air flow through the living area section and higher air velocity near the unit's floor in the two cases with balconies (Case 2 and Case 3). It also explains the highest average velocity in the 0.6 m plan for Case 2 and Case 3 compare to the 1.2 m and 1.8 m plans.
- The highest average velocity in bedroom sections can be seen in Case 2. This is considered to be the result of high pressure in adjacent zones in living area.
- Despite the difference in average velocity in the sections through the bedrooms doors (B), no noticable difference in average velocity in the other sections (C) from the bedrooms is evident among the case studies.

Considering Case 1 as the base case, investigation of ACH shows 24% and 3% less performance in Case 2 and Case 3 respectively. The idealised assumptions that were made in the simulations (i.e. fully open openings) resulted in high number of the ACH. Hence, ACH in the case studies was only discussed relatively to each other.

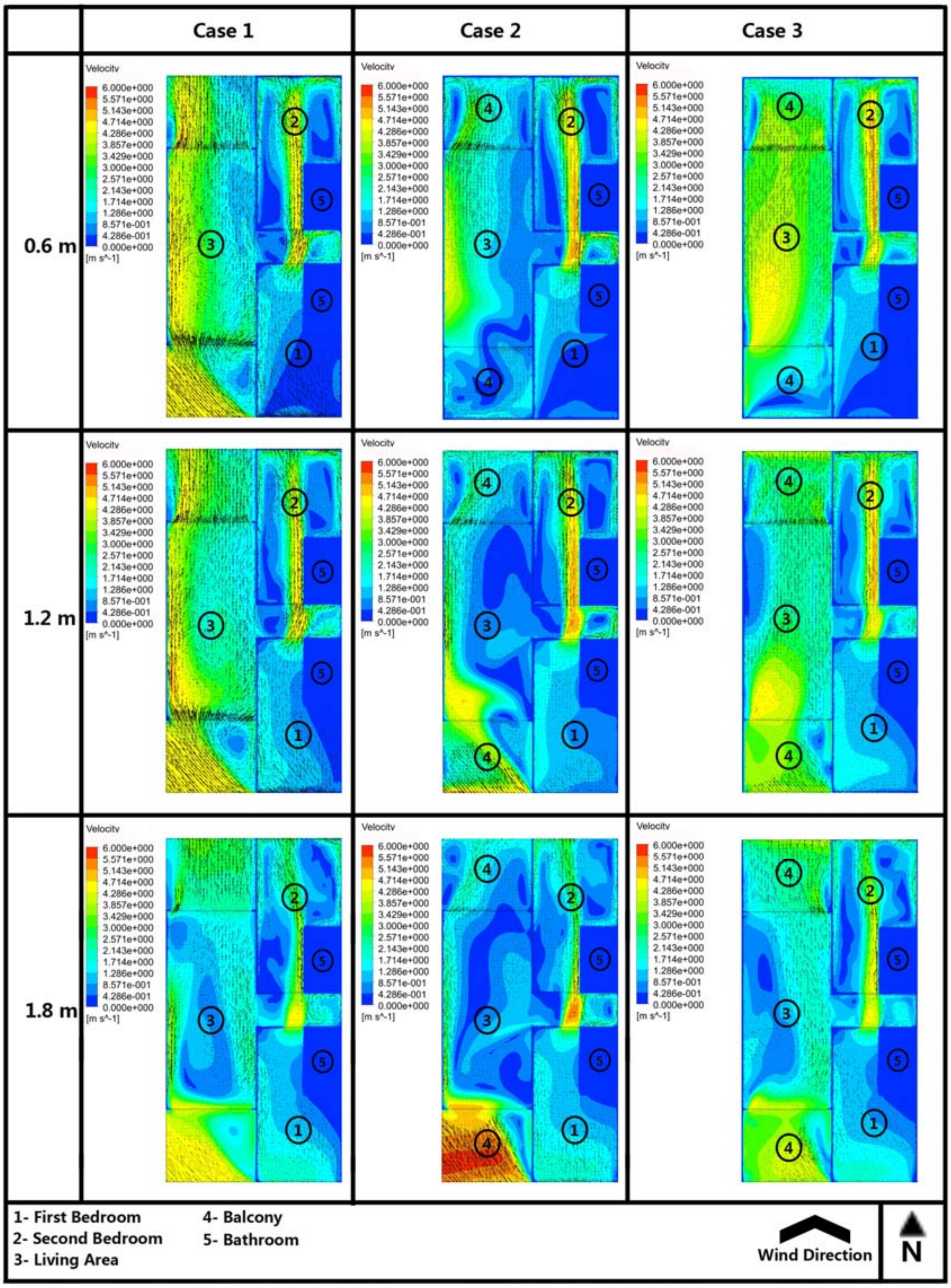

Figure 4: Velocity magnitude at heights of 0.6 m, 1.2 m and 1.8 m for the three case studies.

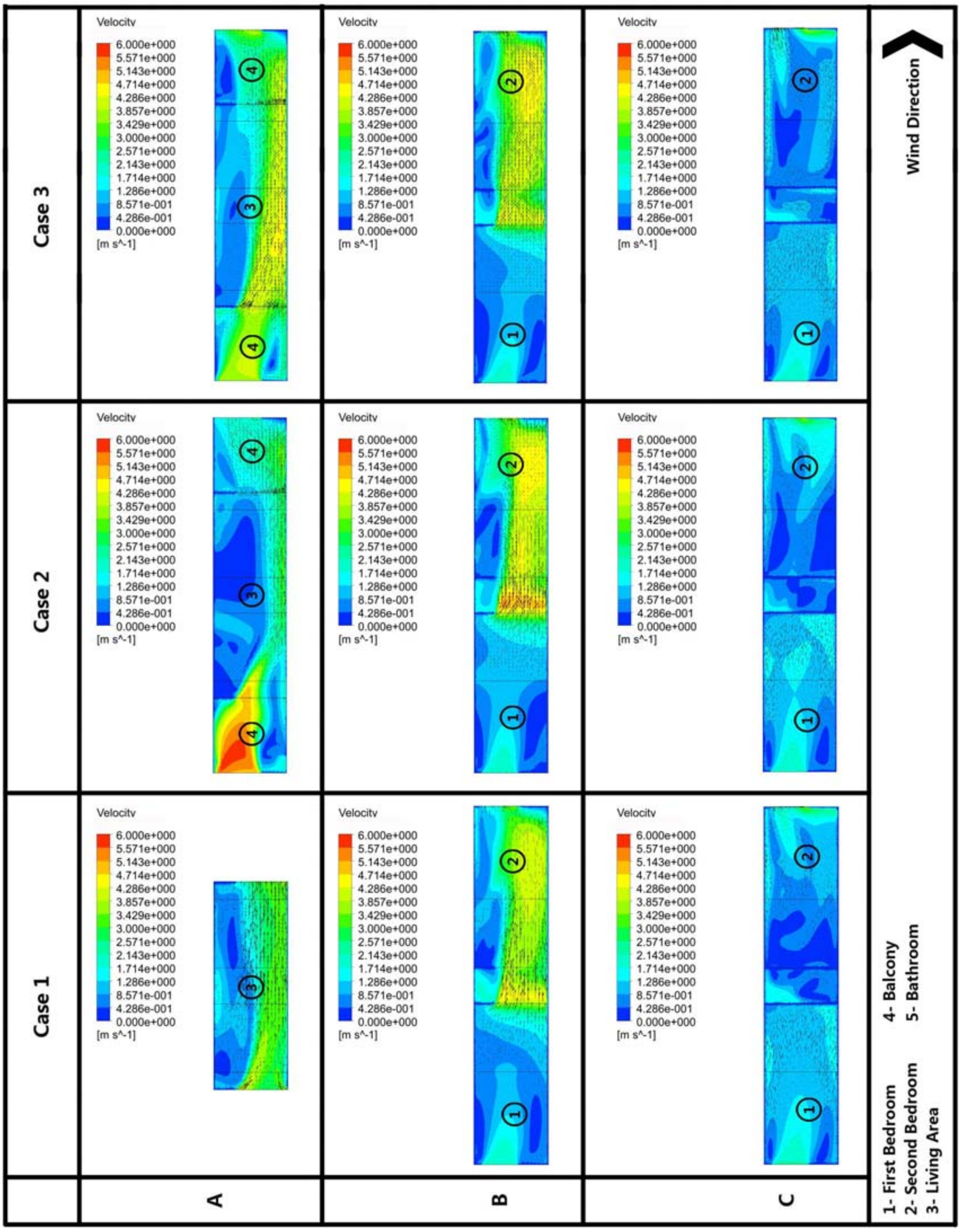

Figure 5: Velocity magnitude on sections through living area, bedroom doors and bedrooms close to western wall.

As can be seen in Table 1, Case 3 has the highest average velocity in the whole unit volume and the lowest average velocity is evident in Case 2.

Table 1: Average velocity in case studies volume

	Case 1	Case 2	Case 3
Average Velocity (m.s^{-1})	1.5	1.3	1.6

5. Conclusion

This study investigated the influence of the provision of balconies in high-rise residential buildings in subtropical climates using CFD as an analysis method. ACH, flow uniformity and average velocity were used as criteria to assess ventilation performance of three case studies.

Among the three examined case studies, Case 3 with the semi-enclosed balcony had the best performance in terms of flow uniformity and average velocity. Case 2, however, with an open balcony had the worst performance in all defined criteria. Although the amount of ACH in Case 1 is slightly higher than that of in Case3, taking into account other criteria, it can be suggested that integrating the semi enclosed balconies into high-rise residential buildings would enhance the ventilation performance at 0° wind incidence. However, further studies need to be done considering various wind angles.

This study assessed the air flow at three different levels regarding human body height while sleeping, sitting and standing. The minimum air movement observed in the bedrooms at the height of 0.6m emphasises on the importance of designing openings sill height or other design considerations regarding the space function and the human body height for intended activities in each space.

These results contribute to the understanding of the effect of three different balcony types on natural ventilation in high-rise residential buildings given the limited body of literature in this area.

6. Limitations and Future work

In the presented analysis, some simplifications and assumptions were made to limit the influential variables, such as modelling the whole apartment building as a bulk without any openings except for the unit of interest, assuming the openings are fully open and not considering surrounding buildings. These simplifications may have led to idealizing the simulation results and higher air velocity and hence, higher ventilation rate. However, as the main purpose of this study is to compare the effect of three different balcony types, these idealizations may have limited effect on the outcomes as the relative values were considered rather than absolute values. This paper is a part of an ongoing study and simulation validation through full-scale measurements will be the next step. Investigation of various wind angles and different opening configurations will be also undertaken.

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