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Numerical simulation of single-sided natural ventilation: Impacts of balconies opening and depth scale on indoor environment

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Abstract. Heating Ventilation and Air Conditioning (HVAC), including, Mechanical ventilation (MV) in the building sector accounts for around 40% of electricity consumption and a large percentage of Greenhouse Gas (GHG) emissions. Natural ventilation (NV), as an alternative method, assist in decreasing energy consumption as well as harmful emissions. Balconies, a common architectural element in high rise residential buildings, could enhance NV and reduce reliance on mechanical ventilation in cooling dominant climates. Indoor air velocity and distribution, IAV and IAD, due to NV is less predictable than MV, and the impacts of balcony geometry on IAV and IAD profile have not yet been classified. This study, focusing on single-sided ventilation apartments, seeks to determine to what extent balcony depth and door opening area impacts on the indoor environment of the attached living area. For this, 3D – steady-state Computational Fluid Dynamics (CFD) simulations were conducted using ANSYS Fluent. The simulation results were validated against measured data in a full-scale experimental study in a residential building in subtropical Brisbane, Australia. Five different openings and nine depth scenarios were modelled, with results showing variances in indoor mean air velocity and temperature. The outcomes reveal the impacts of opening and depth scales on IAD profile, as well as IAV and temperature magnitude at the attached indoor area. Although the defined scenarios could not reach a firm conclusion, the findings of simulation reject the shallowest balcony scenario (depth less than 2 m) due to weak IAD. Besides, the results show that a small opening could lead to an acceptable IAV at the attached indoor area. Results also suggest that further research on the indoor distribution of temperature and air velocity, consequently neutrality based on thermal comfort model, may provide further clarity on the effect of geometric factors on occupant comfort through NV.

Keywords: Natural Ventilation, CFD, Balcony, Geometry, Indoor Air Distribution (IAD), Residential

1. Introduction

As a large percentage of greenhouse gas emissions is attributed to mechanical ventilation (MV) and cooling, obtaining green alternatives to MV is compelling [1]. Natural ventilation (NV) was historically used for cooling, before industrialisation and the rise of modern air conditioners [2]. In modern architecture, façade design that includes the provision of balconies is one of considered element for NV to reduce energy consumption [3, 4]. The provision of balconies affects indoor airflow distribution (IAD) and Indoor Air Velocity (IAV) that affects the quality of the attached indoor area and thermal comfort. Some studies have revealed the key role and influences of geometric factors of balcony (i.e. depth scale) on the indoor environment [5, 6]. A few studies focused on the balcony' effects on NV,

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while other common architectural a large number of studies were published on other elements, particularly windows [7]. Although both windows and balconies are typically employed in residential apartments in different climate zones all around the world, there are only a few studies that studied the impacts of balconies' geometry on performance of NV and thermal comfort under NV mode [8].

The current article aims to investigate the balcony geometry -depth and door opening area – effects on the indoor environment in a single-sided naturally-ventilated unit. For this purpose, this study scrutinies the effects balcony opening and depth sizes on NV (IAV, IAD, and temperature) in the attached indoor area. The authors carried out a full-scale in-situ experiment to set up and valid Computational Fluid Dynamics (CFD) simulation. The validated simulation, then, employed to compare the defined configuration tests to explore balcony opening and depth sizes impacts. This article describes the case study and the experiment design, as well as the CFD simulation details in Section 2. Then, Section 3 presents and analyses the results of different scenarios numerically (IAV and temperature) and graphically (IAD) to illustrate the impacts of different opening and depth sizes on NV. Finally, this study concludes from the results and suggests for future research are shown in Section 4.

2. Methodology

2.1. Full-scale experimental design - case study

The in the subtropical climate of Brisbane, Australia (-27.4723 ° S, 153.0374 ° E) is a two-bedroom residential unit (apartment) with openings connecting the balcony to the living room and the main bedroom. The unit is on the 8th floor of a 13-storey residential building which is not surrounded or blocked by other buildings. The balcony doors are the only source of ventilation (i.e. Single-Sided Ventilation (SSV)). This study only examined the balcony and its connection to the living room (i.e. all internal doors and the balcony door to the bedroom were closed.) The experiment was carried out in three weeks from December 22nd, 2018 and January 9th, 2019. Airspeed direction and magnitude, Relative Humidity (RH), and Temperature (T) were measured in various locations (Figure 1) using three anemometers (3D WindMaster, 2D WindSonic, and Kestrel 4500 Weather Pocket), three RH sensors, and 17 T sensors (HOBO and Maxim iButtons). All equipment was mounted at 1.2 m above floor level, to represent a seated.

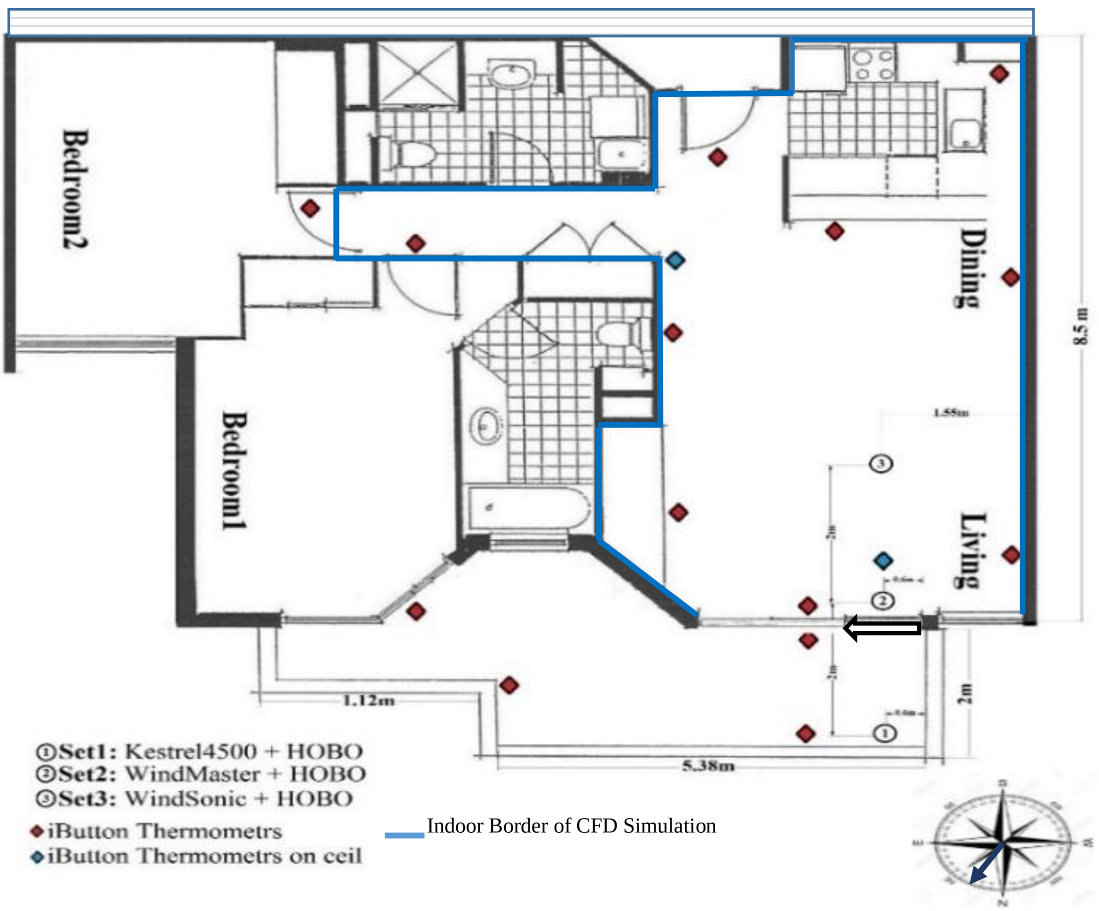

Figure 1. Locations of the sensors on the unit layout

2.2. CFD simulation

CFD modelling numerically find the air movement specifications using Reynolds-Averaged Navier-Stokes (RANS) and the RANS model has been extensively applied to simulate the indoor environment [9] or outdoor spaces such as a balcony [10]. ANSYS Fluent V19.0 was recruited to reveal the effects of possible configuration tests on indoor airflow and temperature at the indoor area using 3D RANS model. This study used ANSYS Fluent V19.0. The computational domain size was selected based on the best practice guideline [11] and was defined based on the height of the building (h) - 42 m. The upstream, downstream, lateral, and height of the domain (H) are 3h, 15h, 3h, 3h, and 6h, respectively. The computational domain excluded other high-rise buildings. An unstructured grid with tetrahedral volume was generated using ANSYS ICEM CFD R19.0. The grid was refined for the surfaces of building, unit, and opening, and the most refined mesh was dedicated to the opening, and adjacent walls with the unit surface of 1e-2 and 5e-2 m, respectively. Grid sensitivity analysis was carried out with 6, 11, and 18 million elements for coarse, medium, and fine scenarios, respectively. Based on a comparison between fine and medium, and medium and coarse scenarios (3.8% and 6.6% difference, respectively), the medium mesh was considered for the simulation.

The simulation boundary condition was set on velocity inlet, outflow for outlet boundary, symmetry for top and lateral boundary of the computational domain, and walls surfaces and ground as wall boundary. The inlet velocity was considered using the Weibull function:

$$V_h = V_r \left(\frac{h}{h_r}\right)^{\alpha}, \;\; \alpha = 0.35 \; is\ the\ terrain\ roughness\ in\ Brisbane\ CBD \qquad (1)$$

where V_h is the velocity inlet profile related to a specific height, and V_r and h_r represent the velocity and height at the wind station, as the simulation reference. The terrain roughness is shown by (α), and is 0.35 for Brisbane CBD [12]. Renormalisation Group (RNG) k-ε with enhanced wall treatment was the RANS model used in this NV study, based on [13, 14]. The operating and wall temperatures were defined as the most frequent temperature of the Brisbane CBD, for the specific months, based on the last 20 years of data (24.1 ℃).

The CFD model was validated against the in-situ measurement. For this, the velocity inlet was obtained using average wind velocity from the meteorological weather station for the experiment period and the Weibull function. Wind velocity was extracted for the exact period of the in-situ experiment, using the average wind speed as V_r and h_r=8.2 m (the height of Brisbane wind station). For validation, the weather station data was compared with the experimental data, adjusted to capture the indoor air velocity vector. The validation results show that the differences between simulation results and experiments are 6.45%, 10.90%, and 4.69% in Kestrel, WindMaster, and WindSonic, respectively. The Root Mean Square Error (RMSE) was 2.79%.

3. Results and discussion

Table 1 shows the five examined scenarios of balcony door opening (Width (W), Height (H)) and the nine scenarios of balcony depth (Depth of the balcony (D) to Length of the attached space) compared with the experimental unit. The impacts of door opening area and balcony depth are shown in IAV (m/s) and temperature (℃). The highest IAV occurred in the smallest opening, but the lowest temperatures were obtained with the largest door opening. In the balcony depth scenarios, the highest and lowest IAV occurred, respectively, in scenarios 5 and 4, while the highest and lowest temperature was obtained in scenarios 4 and 7. The results show that while door opening area and balcony depth have an impact on IAV and indoor temperature, no clear recommendations can be made about balcony geometry to improve NV.

Table 1. A comparison of the simulation results of different opening and depth scales

Test Configurations		H (m)	W (m)	W/H (%)	D (m)	IAV (m/s)	Average of Temperature (℃)
Opening Scenarios	Scen1	2.4	0.9	37.5 %	2	0.488	25.580
	Case Study	2.4	1.1	45.8%	2	0.120	25.423
	Scen2	2.4	1.2	50 %	2	0.156	25.296
	Scen3	2.4	1.5	62.5	2	0.181	25.121
	Scen4	2.4	1.8	75%	2	0.160	25.167
	Scen5	2.4	2.4	100%	2	0.221	25.016
Test Configurations		**D (m)**	**L (m)**	**D/L (m)**	**W (m)**	**IAV (m/s)**	**Average of Temperature (℃)**
Depth Scenarios	Scen6	4.25	8.5	50%	1.1	0.149	25.348
	Scen7	3.825	8.5	45%	1.1	0.119	25.435
	Scen8	3.4	8.5	40%	1.1	0.125	25.331
	Scen9	2.98	8.5	35%	1.1	0.109	25.685
	Scen10	2.55	8.5	30%	1.1	0.161	25.378
	Scen11	2.125	8.5	25%	1.1	0.110	25.510
	Case Study	2	8.5	23.5%	1.1	0.120	25.423
	Scen12	1.7	8.5	20%	1.1	0.148	25.207
	Scen13	1.275	8.5	15%	1.1	0.139	25.438
	Scen14	0.85	8.5	10%	1.1	0.115	25.366

For a better understanding of the impacts of geometry on IAD in the defined opening and depth scenarios, airstreams between 0 and 2.4m (ceiling height) were drawn using Tecplot 360 EX 2015 R2, shown in Figure 2 and Figure 3.

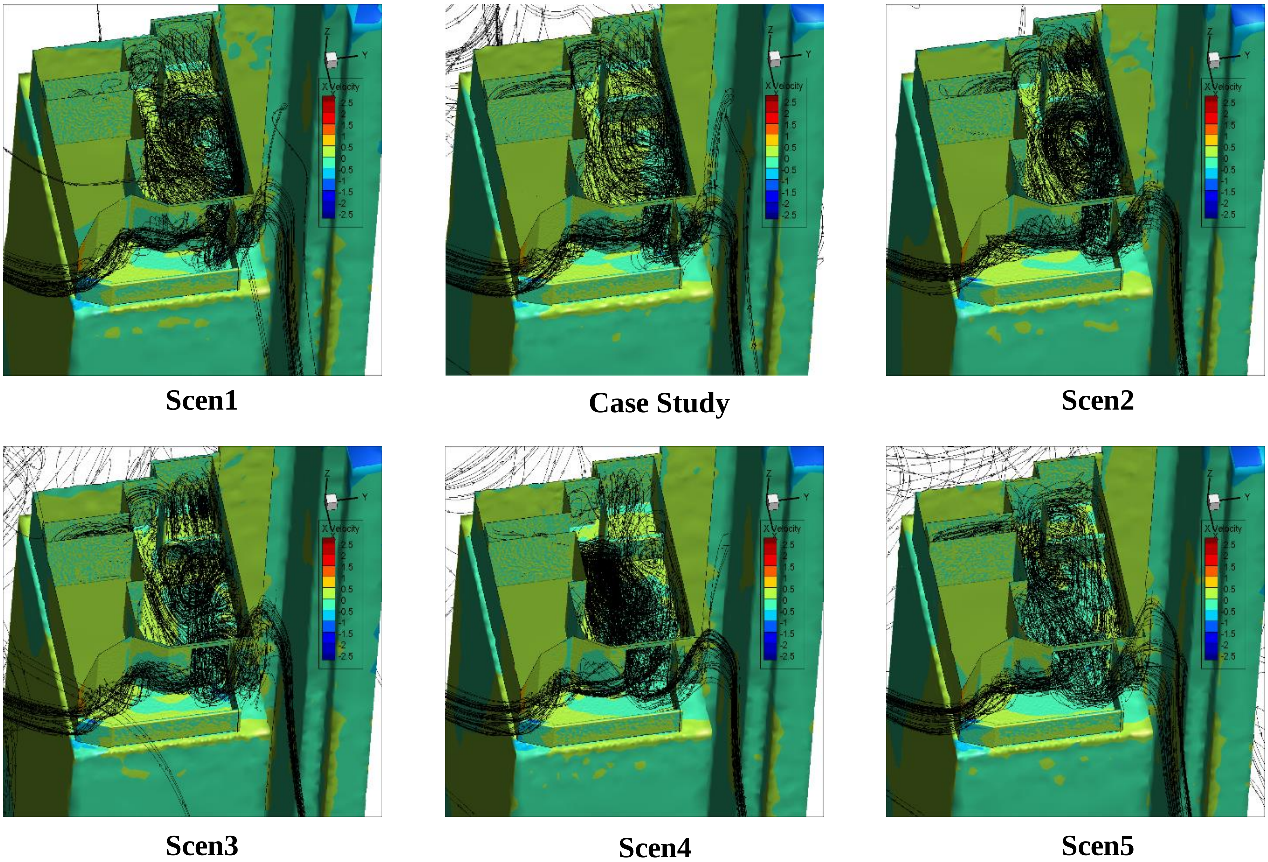

Figure 2. Comparison of IAD using streamlines in defined opening scenarios

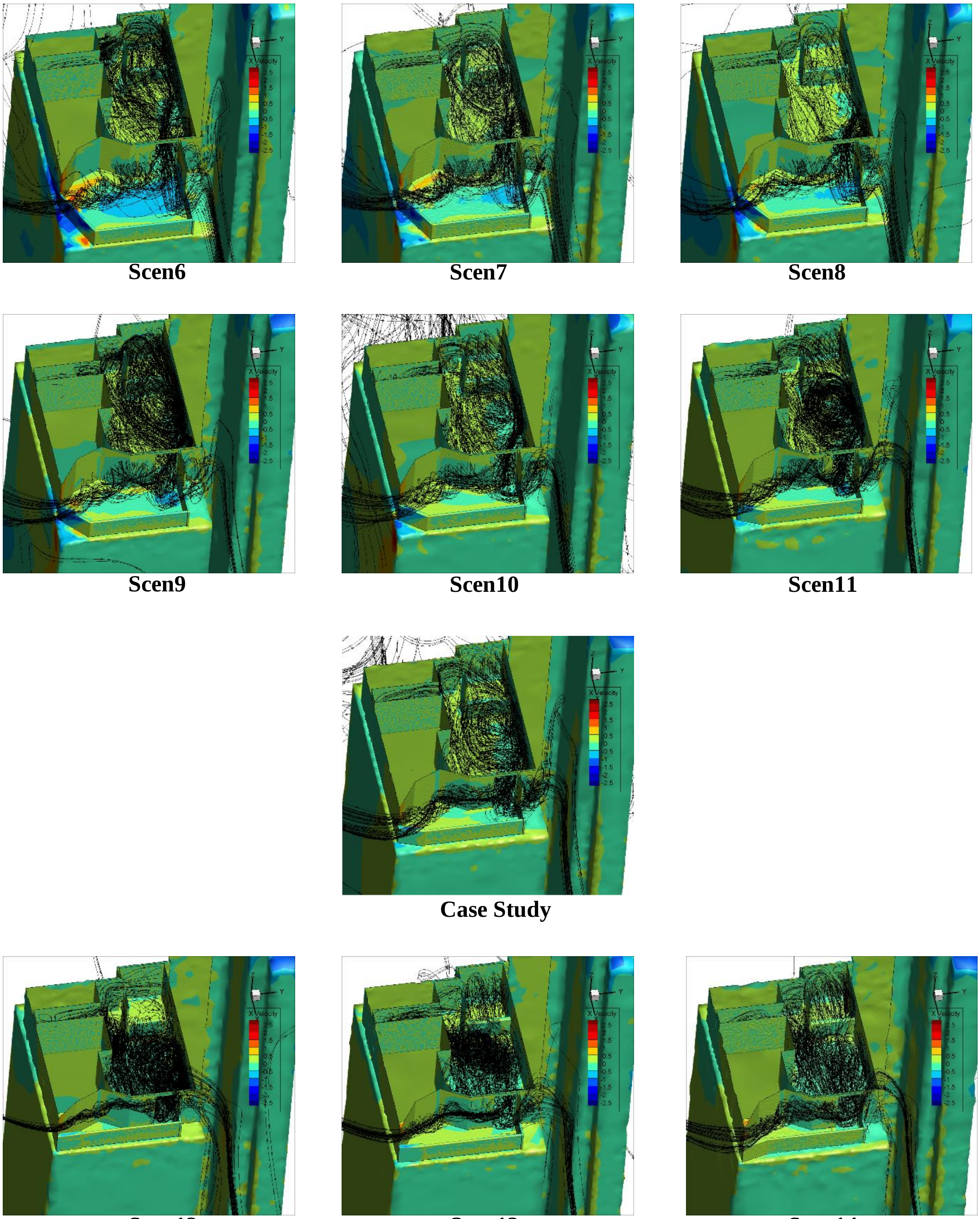

Figure 3. Comparison of IAD using streamlines in defined depth scenarios

Figure 2 and Figure 3 highlight the impact of opening and depth sizes on the IAD and uniformity of air mixing, which are two main factors for indoor air quality [15]. Figure 2 does not show a firm conclusion of opening size impact on IAD. Scenario 3 and 4 show the weak distribution of air and strong turbulence occurred in the left size of scenario 4. Figure 2 also displays some spots without any breeze in the scenarios with larger opening such as Scen4.

Figure 3 shows configuration tests with smaller balcony size (i.e. Scen12) led to some areas without any breeze, while the opening size, so the volume of internal air, is fixed in all scenarios. Figure 3 displays that weak air distributions happened in scenarios with shallow balconies (Scen12, Scen13, and Scen14). Furthermore, these scenarios with less than 2 m depth size, which are not suggested by national standards [16, 17], led to some regions without any breeze, as well as some other parts with turbulence, which reduce the quality of NV at the indoor area.

Overall, the comparison of the air distribution at an indoor area in the defined scenarios highlight that there is no clear conclusion on the impacts of opening and depth scales on the air distribution and NV performance in an extended view. Modelling the indoor distribution of temperature and air velocity, as well as thermal comfort, may add further clarity to the impact of NV on occupant comfort and hence inform the selection of optimal balcony geometries.

4. Conclusion

The present article used CFD simulation, validated against experimental data from a subtropical SSV apartment, to investigate the impacts of balcony door opening area and balcony depth scenarios on IAV and temperature. The results reveal that door opening area and balcony depth do affect the IAD, IAV and average indoor temperature, although trends and precise outcomes could not be determined. The IAD profiles and average IAV reveals that small opening might play a role as a nozzle and transfer recirculation far from opening and thus reduce exterior air. The shallowest depth scales ($D < 2$m) may lead to a non-uniform and unstable IAD. Further research to look at the IAD, IAV and thermal comfort (variations of neutrality in different cases) may be helpful in providing further clarity on the implication of balcony geometry on NV for occupant comfort.

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