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 (IAV) and distribution due to NV is less predictable than MV, and the impacts of balcony geometry on IAV and distribution 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 suggest that further research on the indoor distribution of temperature and air velocity may provide further clarity on the impact of balcony geometry 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, finding low or zero-carbon alternatives to MV is compelling [1]. Natural ventilation (NV) was historically used for cooling, before industrialisation and the rise of Heating Ventilation and Air Conditioning (HVAC) technologies [2]. In modern architecture, façade design that includes the provision of balconies remains one of the leading approaches for NV to reduce energy consumption [3, 4]. A balcony is perceived by residents as one the most desired features for providing fresh air, particularly in cooling dominant climates [5]. The provision of balconies affects outdoor and indoor airflow profiles and Indoor Air Velocity (IAV) and distribution that effects the indoor environment and thermal comfort. Some studies have revealed the critical role and importance of balcony features such as opening and depth size on the indoor environment [6, 7].

Far fewer studies have been published relating to the role of balconies for NV, compared with most other design elements, and in particular compared to windows [8]. This is curious given that windows and balconies are two commonly used elements in medium and high-rise residential buildings in multiple climate zones and cultures globally. There are only a few studies that have investigated the impacts of balconies' features on NV performance [9]. The current article, hence, aims to investigate the impacts of geometry features - balcony depth and door opening area - on the indoor environment in a single-sided naturally-ventilated unit.

2. Methodology

2.1. Full scale experimental design - case study

The case study 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 Dec 22th 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 person.

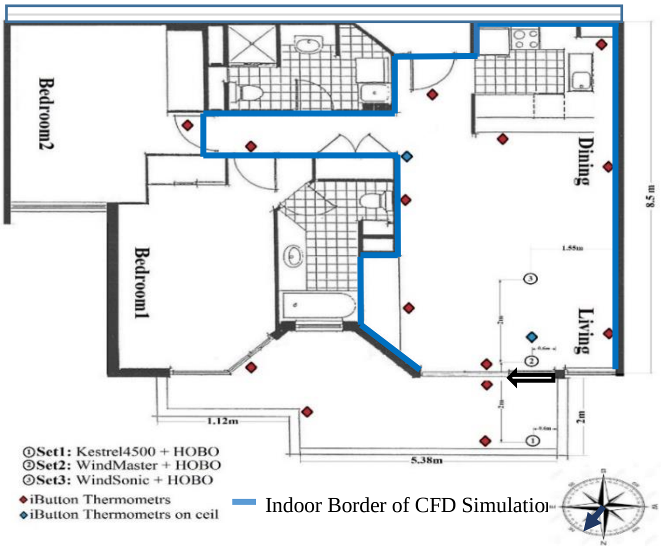

Figure 1. Locations of the sensors on the unit layout

2.2. CFD simulation

CFD simulation software numerically describes the physics of air movement using Reynolds-Averaged Navier-Stokes (RANS) and the RANS model has been extensively applied to simulate the indoor environment [10] or outdoor spaces such as a balcony [11]. 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 [12] 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 unit surfaces 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:

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

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 [13]. Renormalisation Group (RNG) k-ε with enhanced wall treatment was the RANS model used in this NV study, based on [14, 15]. 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 ºC).

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 5 examined scenarios of balcony door opening (Width (W), Height (H)) and the 9 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 (ºC). 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. Modelling the indoor distribution of temperature and air velocity may add further clarity to the impact of NV on occupant comfort and hence inform the selection of optimal balcony geometries.

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

Size details		**H (m)**	**W (m)**	**W/H (%)**	**D (m)**	**IAV (m/s)**	**Average of Temperature (ºC)**
Opening	**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
Size details		**D (m)**	**L (m)**	**D/L (m)**	**W (m)**	**IAV (m/s)**	**Average of Temperature (ºC)**
Depth	**Scen1**	4.25	8.5	50%	1.1	0.149	25.348
	Scen2	3.825	8.5	45%	1.1	0.119	25.435
	Scen3	3.4	8.5	40%	1.1	0.125	25.331
	Scen4	2.98	8.5	35%	1.1	0.109	25.685
	Scen5	2.55	8.5	30%	1.1	0.161	25.378
	Scen6	2.125	8.5	25%	1.1	0.110	25.510
	Case Study	2	8.5	23.5%	1.1	0.120	25.423
	Scen7	1.7	8.5	20%	1.1	0.148	25.207
	Scen8	1.275	8.5	15%	1.1	0.139	25.438
	Scen9	0.85	8.5	10%	1.1	0.115	25.366

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 IAV and average indoor temperature, although trends and precise outcomes could not be determined. Further research to look at the distribution of IAV and temperature may be helpful in providing further clarity on the implication of balcony geometry on NV for occupant comfort.

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