Investigation of ventilation performance in the multi-story building with various envelope features: Scaled outdoor experiments

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Abstract

Previous research was limited to flat-faτade buildings when evaluating the indoor and outdoor ventilation performance in a multi-story building. However, envelope features can provide the shading effect to induce the temperature difference between surfaces exposed to direct solar radiation and those without solar radiation. This temperature difference between surfaces can enhance the thermal buoyancy and change indoor and outdoor ventilation performance. We conducted scaled outdoor experiments to examine the impact of various envelope features on indoor and outdoor ventilation performance in multi-story buildings. Compared to the flat-faτade multi-building, the average normalized horizontal airflow velocity of overhang, small wing wall, and large wing wall multi-buildings increased by 12.41%, 10.56%, and 5.56%, respectively. Cross-ventilation is more susceptible to envelope features than single-sided ventilation in air change per hour (ACH). Specifically, the ACH values of cross-ventilation for large wing wall, small wing wall, and balcony multi-buildings decreased by 69.98%, 25.79%, and 12.12% relative to the flat-faτade building. For the same envelope feature building, the ACH values of single-sided ventilation on the windward side are better than those on the leeward side, particularly the building with small wing walls, with an improvement of 12.77% compared to flat-faτade. This study contributes to advancing the understanding of urban ventilation, and provides a valid basis for designing envelope features in urban buildings.

Keywords: multi-story building, envelope features, scaled outdoor experiment, wind momentum and thermal, buoyancy effect, ventilation performance, air change per hour (ACH)

1. Introduction

The sustainable development strategy proposed by the United Nations has gained traction in several fields as urban environments become increasingly hostile (Tsai 2022). Green building is a crucial objective in sustainable development strategies, as it effectively alleviates environmental issues like global warming, building energy consumption, air pollution, etc. (Ding et al. 2021; Cao et al. 2022; He et al. 2024).

Envelope features (i.e., balconies, horizontal features, vertical features, and adjustable features) are crucial in green building design. These features can provide shading, reduce noise, and improve ventilation (Mak et al. 2005; Aflaki et al. 2015; Nejat et al. 2018; Tong et al. 2019; Cui et al. 2020; Cui et al. 2021; Harris 2021; Rathore et al. 2022; Cui et al. 2024a). Therefore, it is crucial to examine how the geometrical characteristics of envelope features impact near-façade wind flow, wind comfort, and infiltration in buildings (Niu 2004; Mak et al. 2007; Blocken and Carmeliet 2008; Ai et al. 2011; Hong and Kim 2016; Omrani et al. 2017). Previous research discovered that envelope features can effectively affect the near-façade wind flow and convective heat exchange on the exterior surface of buildings (Montazeri and Blocken 2013; Cui et al. 2018). They also can alter air penetration and movement, which improves ventilation performance in street canyons (Jiang et al. 2019a; Jiang et al. 2019b; Kahsay et al. 2019). Ai and Mak (2018) investigated single-sided ventilation in buildings with different envelope features and found that horizontal envelope features effectively drive indoor natural ventilation in buildings. Aflaki et al. (2015) found that vertical envelope features affect indoor air velocity to enhance ventilation performance in tropical climates. Moreover, wing walls significantly increased the pressure difference across the openings to improve indoor ventilation in single-sided ventilation, resulting in a higher hourly air change rate (Mak et al. 2007; Xie et al. 2007; Ai and Mak

2018). Cross-ventilation is much more effective in buildings with balconies than single-sided ventilation (Omrani et al. 2017). Compared to flat-façade canyons, the balconies in step-up and step-down canyons decrease the air change rate per hour (ACH) by 89% and 94.4%, respectively (Sin et al. 2023). Previous studies on natural ventilation were limited to wind momentum. However, it is imperative to consider the thermal buoyancy effect, especially when wind conditions are relatively weak.

As urban buildings become denser and urban wind speed diminishes, the pressure differences around buildings decrease. Under certain weather conditions, the building surface temperature difference between surfaces exposed to direct solar radiation and those not exposed can reach 19 °C (Santamouris et al. 1999). Therefore, the thermal buoyancy effect becomes a driving force in building natural ventilation when substantial differences exist (Ai and Mak 2018). The impact is more pronounced in high-density urban areas than in rural areas (Cheung and Liu 2011). Moreover, single-sided ventilation is a more common ventilation mode than cross-ventilation in high-density cities. Single-sided ventilation is intricate and is affected by the turbulence of the incoming wind and the bidirectional airflow interactions at the opening (Haghighat et al. 1991; Linden 1999; Haghighat et al. 2000; Ai and Mak 2014). However, envelope features provide a shading effect and create a great temperature difference between the indoor areas and the building façade. The temperature difference affects the turbulence characteristics and can further impact ventilation performance (Xie et al. 2007; Dallman et al. 2014; Liang et al. 2024). Previous studies on natural ventilation based on wind momentum have predominantly relied on CFD simulations and wind tunnel experiments (Cui et al. 2019). When wind momentum and thermal buoyancy effect are both significant in urban airflow, it is difficult to achieve the independence requirement of the Richardson number (*Ri*) and Reynolds number (*Re*) in wind tunnel experiments because the wind tunnel experimental scaled models require a great temperature difference between the building model façade and air (≈100 °C). The scaled outdoor experiment is a better choice for investigating ventilation performance, as it can adhere to thermodynamic similarity requirements and provide more realistic climatic conditions (Kanda et al. 2005; Kanda 2006; Kawai and Kanda 2010; Hang and Chen 2022). Nakamura and Oke (1988) used scaled outdoor experiments to examine wind-thermal environments under various conditions in street canyons. Previous research also used scaled outdoor experiments to examine the impacts of different envelope features on wind-thermal environment and pollutant exposure in street canyons (Cui et al. 2024a; Cui et al. 2024b). However, they did not explore the impact of envelope features on the indoor and outdoor ventilation performance in multi-story buildings under actual atmospheric environments.

In this context, the following issues were mainly addressed in this study:

1) When wind momentum and thermal buoyancy effect are both significant in urban airflow, how did different envelope features in a multi-story building affect the ventilation performance?
2) The bulk Richardson number (*Ri*b) was utilized to evaluate the relative significance between the thermal buoyancy effect and wind momentum on airflow. This analysis of the *Ri*b aims to identify

which types of envelope features were most influenced by the wind momentum and thermal buoyancy effect.

3) The air change rate per hour (ACH) was also utilized as a metric to examine the influences of various envelope features on indoor ventilation. Additionally, this study compared the impact of the same envelope feature on cross-ventilation and single-sided ventilation in a multi-story building.

The remaining sections of this manuscript are organized as follows: Site description and measurement setup, similarity criteria, and data analysis methods are described in Section2. Section 3 presents the results and discussion. Section 4 addresses the limitations and future work. Finally, Section 5 summarizes the conclusions.

2. Methodology

2.1. Site description and experimental setup

The SOMUCH experimental platform is situated south of Guangzhou, China (23°4′ N, 113°23′ E), which is the humid subtropical climate zone (Köppen climate classification: Cfa). The SOMUCH is positioned distant from other buildings to eliminate their impact on the local wind flow, ensuring higher accuracy in the study (Figure 1) (Chen et al. 2020a; Zheng et al. 2023). It can meet geometrical and dynamical similarities between scaled models and full-scale buildings (Wang et al. 2021). Previous researches have validated the reliability of SOMUCH (Chen et al. 2023; Liang et al. 2024) and investigated the effects of ventilation performance (Chen et al. 2020b), thermal buoyancy (Chen et al. 2020b; Cui et al. 2024b), thermal storage (Chen et al. 2020a), and vertical greening (Zheng et al. 2023) on the wind-thermal environment in SOMUCH.

The scaled outdoor experiments were conducted on May 24 and June 17, 2019 (typical summer climate in subtropical regions). The hollow building models (wall thickness = 0.015 m) are constructed from concrete and painted in dark gray. The ratio between the building model ($L \times W \times H$ = 0.5 m × 0.5 m × 1.2 m) and the full-scale building is 1:10. Two groups of ultrasonic anemometers were placed on the lateral and windward sides to record the wind speed. No other building models surrounded the multi-story building moldel (Figure 2). On each floor, three windows (0.07 m × 0.07 m) were meticulously installed at building heights of 1.0, 0.6, and 0.1 m. Moreover, various envelope features were set up at different heights of the building (Figure 3). These features were made of plastic and adhered to the scaled model surface with Scotch tape.

During the scaled outdoor experimental period, a weather station (Rain Wise Port Log) was installed at a height of 2.4 m to record background data (i.e., wind speed, wind direction, air temperature, solar radiation, and air humidity) at 1 min intervals. All data recorded by the weather station were averaged over 5 min. Ultrasonic anemometers recorded the three-directional velocity components at a frequency of 20 Hz: *u* (parallel to the multi-story building), *v* (across the multi-story building), and *w* (perpendicular to the multi-story building). Two groups of ultrasonic anemometers (Mast 1 and Mast 2) were placed in the northwestern and southeastern of the multi-story building model to measure background wind speed. Mast 1 was installed at heights of 0.6, 1.2, and 2.4 m, while Mast 2 was set up at heights of 0.6, 1.2, 2.4, 5, and 10 m. Additionally, two groups of ultrasonic anemometers were positioned around the building model to record the velocity. Mast 3 was situated on the windward side of the building at heights of 0.2, 0.6, 1.0, and 2.4 m. Mast 4 was situated on the lateral side of the building at heights of 0.2, 0.6, and 1.0 m. Thermocouples were categorized into two groups. The first group was centrally placed at a height of 0.6 m to measure the temperature of the building surface. The second group was set up at heights of 0.6 and 1.2 m to measure the background air temperature (Figure

3). All temperature data were recorded at 3 s intervals using a data logger. Table 1 shows detailed information on the experimental instruments.

The indoor ventilation performance was evaluated by the ACH in this study. Three windows (0.07 m × 0.07 m) were installed on each side of the building at heights of 1.0, 0.6, and 0.1 m for testing. Additionally, three different types of ventilation were tested in this study: cross-ventilation, single-sided ventilation on the windward side, and single-sided ventilation on the leeward side (Figure 4).

The tracer gas concentration decay method is widely conducted to evaluate the air change rate and airtightness of multi-story buildings (Cui et al. 2015; Zhao et al. 2021; Fellini et al. 2022; Guo et al. 2023). Ethane has been widely used as the tracer gas to evaluate indoor ventilation performance since the density of ethane is close to that of air. Moreover, it is present in the atmosphere at relatively low background levels, which makes it easier to detect its concentration changes and minimize interference (Toscano et al. 2021; Carlo et al. 2024). At the beginning of the experiment, all windows were kept closed, and tracer gas was subsequently introduced into the multi-story building. The gas monitor meticulously recorded tracer gas concentration before and after the experiment. The initial concentrations ($C0$) were recorded before the windows were opened, and the final concentrations (Ct) and experimental time (t) were recorded after allowing time for the concentration to stabilize. Each case was subjected to two experiments. The relevant expression for concentration changes and air changes are defined as Equation (1):

Based on Equation (1), the ACH is calculated using Equation (2) (Dai et al. 2020; Reda et al. 2023): where ACH is the air change per hour, t is the testing time (h), $C0$ is the initial concentration of the tracer gas (ppm), and Ct is the decreased concentration of the tracer gas at t time (ppm).

2.2 Similarity criteria

The scaled models and the full-scale buildings achieved similarities regarding geometry and dynamics, so the scaled models effectively represent the full-scale buildings (Kanda 2006; Oke et al. 2017). The scaled models (*H*~1 m) use real urban materials and are in real boundary conditions that can satisfy the similarities regarding radiation and thermal inertia (Kanda et al. 2005; Pearlmutter et al. 2005; Kanda 2006; Pearlmutter et al. 2007). To replicate the thermal characteristics of actual urban areas, the scaled models in SOMUCH were constructed from concrete materials (Allegrini et al. 2013; Chen et al. 2020a). In the previous studies, the similarities of radiation and thermal inertia in SOMUCH were examined (Chen et al. 2020a; Wang et al. 2021; Lu et al. 2023; Zheng et al. 2024).

To evaluate the validity of the scaled models, the Reynolds number (*Re*) can be used as a similarity criterion, which is defined as Equation (3) (Allegrini et al. 2013): where *H* is the multi-story building height, □□*k* is the kinematic viscosity, and *U*ref is the freestream velocity.

When the experimental Reynolds number satisfies the independence criteria, the experimental airflow is considered similar to the real airflow. Chen et al. (2020a) demonstrated that the Reynolds number satisfied the requirement for Reynolds number independence (e.g., *Re* = 164,384 at 2 m/s and *Re* = 41,096 at 0.5 m/s) in SOMUCH. Figure 5 shows the experimental Reynolds numbers outside the multi-story building in this study, in which all data meet the Reynolds number independence requirement. Moreover, the indoor flow patterns should be regarded as similar to the airflow in a full-scale building when the orifice Reynolds number (*Re*o) is up to 5,800 (Chiu and Etheridge 2007; Chu et al. 2011; Jiang et al. 2022). It is sufficient to use the tracer gas decay method for investigating indoor ventilation performance (Dai et al. 2019; Dai et al. 2022; Cui et al. 2023). *Re*o is defined as Equation (4): where *L* is the window height, and *U*o is the orifice velocity.

The tracer gas experiments of each case were conducted multiple times. To meet the indoor Reynolds number independence requirement, we selected a few of them based on the freestream velocity and orifice velocity for further analyzing the ACH in the multi-story building. The data that failed to meet the Reynolds number independence requirement were excluded from the analysis.

Moreover, this study used the bulk Richardson number ($Ri\mathrm{b}$) to evaluate the relative significance of wind momentum and thermal buoyancy on urban airflow. It is defined as Equation (5) (Richards et al. 2006; Cui et al. 2016): where g is the gravitational acceleration, $\beta = 1/T\mathrm{ref}$ is the thermal expansion coefficient, $T\mathrm{ref}$ is the reference temperature, $T\mathrm{w}$ is the façade temperature, H is the multi-story building height, $U\mathrm{ref}$ is the freestream velocity, and $T\mathrm{w}-T\mathrm{ref}$ is the temperature difference between the building façade and the air. For $Ri\mathrm{b} < 0.1$, the wind momentum dominates airflow. For $Ri\mathrm{b} \approx 1$, the thermal buoyancy and wind momentum are both significant in urban airflow (wind momentum and thermal buoyancy dominance). For $Ri\mathrm{b} \geq 10$, thermal buoyancy dominates airflow (Liang et al. 2024). However, thermal buoyancy dominated urban airflow ($Ri\mathrm{b} \geq 10$) infrequently occurs in scaled outdoor experiments as it fails to meet the Reynolds number independence requirement (Kanda 2006).

2.3 Data analysis method

Figure 6 shows the wind direction map of multi-story buildings, which defines the freestream in parallel, across, and perpendicular. The velocity magnitude (Uspeed) was also investigated to examine building ventilation. To mitigate the influence of inconsistent experimental periods on the results, we used the temporal-averaged normalized wind speed component $u/U\mathrm{ref}$, $v/U\mathrm{ref}$, $w/U\mathrm{ref}$ (where $u/U\mathrm{ref}$ is the ratio of the wind speed component u to the freestream velocity), and the temporal-averaged normalized horizontal velocity $U\mathrm{speed}/U\mathrm{ref}$ (where $U\mathrm{speed}/U\mathrm{ref}$ is the ratio of the velocity magnitude to the freestream velocity) to evaluate the natural performance of the multi-story building with different envelope features (Chen et al. 2020b).

2.4 Data quality assurance

To assure the reliability and validity of the scaled outdoor experiment, it is desirable to understand the most important sonic anemometer is 1.5% within the 0–50 m/s range. Ultrasonic anemometers recorded three-directional velocity components at a frequency of 20 Hz. The experimental data were averaged over 30 s intervals, with any missing values removed. The outliers (any time series of instantaneous components that deviated by more than ±4 times the standard deviation from the average) were excluded from further analysis. The temporal-averaged wind velocity components were compared to examine the impacts of various features on the wind speed. This method can ensure the validity of experimental data (Chen et al. 2020b; Chen et al. 2021a; Dai et al. 2022).

3 Results and discussion

3.1 Analysis of climate conditions during experimental periods

The multi-story buildings were categorized into five different groups based on their envelope features. On May 24, experiments were conducted at the large and small wing wall multi-story buildings during two different periods, from 10:31 to 14:53 and 17:31 to 20:16. On June 17, experiments were conducted on the flat-façade, balcony, and overhang multi-story buildings during three different periods, from 10:46 to 13:46, 14:11 to 19:05, and 19:21 to 23:54, respectively. To ensure more accurate and consistent results, the background data collected over two experimental days were compared, and the data were processed using normalized parameters, which is a proven approach in the previous literature (Dai et al. 2020; Dai et al. 2022; Bai et al. 2023).

Throughout the two-day experiment, the prevailing wind directions were observed to range from 32.5° to 167.5° and 22.5° to 247.5°, respectively (Figure 7). The wind speed ranged mainly from 0.8 to 3.2 m/s. The background weather station data consistently indicated that the prevailing wind direction originated predominantly from the south. Therefore, the south and north sides functioned as the windward and leeward sides, respectively. The east and west sides functioned as the lateral sides (Chen et al. 2020b; Dai et al. 2022). Overall, the relative humidity ranged from 58% to 93% and the air temperature spanned ranged from 24°C to 32.5°C in the experimental period (Figure 8).

3.2 Analysis of the temporal-averaged wind speed components on the windward and lateral sides

Figure 9 shows the temporal-averaged average normalized horizontal velocity of different wind speed components on the windward sides. For the windward side, envelope features can effectively affect the temporal-averaged average normalized horizontal velocity on the windward side differently for the velocity magnitude (*U*speed) and wind speed components. For the temporal-averaged wind speed component *u* on the windward side, the envelope features decreased the average normalized wind speed component (*u*/*U*ref). The order of impact on the windward side is as follows: large wing wall (21.61%) > small wing wall (17.70%) > overhang (7.82%) > balcony (3.91%). For the temporal- averaged wind speed component *v* on the windward side, the presence of large wing walls, small wing walls, and balconies increased the average normalized wind speed component (*v/U*ref) on the windward side. However, the overhangs decreased the average normalized horizontal velocity by 24.35%. The greatest decreases were 19.17%, 10.54%, and 1.55% for large wing walls, small wing walls, and balconies, respectively. For the temporal-averaged wind speed component *w* on the windward side, the envelope features decreased the average normalized wind speed component (*w/U*ref), except for the balcony increased the *w/U*ref values by 4.54%. The greatest decreases were 18.42%, 9.53%, and 4.26% for overhangs, large wing walls, and small wing walls, respectively. For the temporal-averaged average velocity *U*speed on the windward side, the balconies led to a 0.56% reduction. However, the overhangs, large wing walls, and small wing walls increased the average normalized horizontal velocity (*U*speed/*U*ref) by 12.41%, 10.56%, and 5.56%, respectively. Overall, balconies altered airflow patterns and created multiple areas for separation and recirculation close to the building surface, which weakens the ventilation performance (Montazeri and Blocken 2013; Zheng et al. 2020; Zheng et al. 2021; Zheng et al. 2022; Jon et al. 2023; Tao et al. 2023). Large and small wing walls can utilize the imbalance of the two side flows to improve building ventilation. However, the ventilation performance of large wing walls was better than that of small wing walls. Notably, overhangs can break the upward or downhill flows and create a pressure difference between the above and below area to increase the average normalized horizontal velocity (*U*speed/*U*ref) on the windward side (Ai and Mak 2018; Cui et al. 2018; Cui et al. 2024b).

Figure 10 shows the temporal-averaged average normalized horizontal velocity of different wind speed components on the lateral sides. For the temporal-averaged wind speed component *u* on the lateral side, envelope features decreased the average normalized wind speed component (*u/U*ref). The greatest decreases were 22.09%, 15.72%, 11.92%, and 9.62% for large wing wall, overhang, small wing wall, and balcony multi-story buildings, respectively. For the temporal-averaged wind speed component *v* on the lateral side, small wing walls decreased the average normalized wind speed component (*v/U*ref) by 1.99%. However, the balcony, overhang, and large wing wall increased the average normalized wind speed component (*v/U*ref) by 38.92%, 33.81%, and 8.52%, respectively. For the temporal- averaged wind speed component *w* on the lateral side, envelope features decreased the average normalized wind speed component (*w/U*ref). The greatest decreases were 38.69%, 30.16%, 25.74%, and 5.08% for small wing wall, large wing wall, balcony, and overhang multi-story buildings, respectively. For the temporal-averaged average velocity *U*speed on the lateral side, the presence of large and small wing walls led to 2.28% and 2.26% reductions in the average normalized horizontal velocity (*U*speed/*U*ref). The presence of overhangs and balconies increased the average normalized horizontal velocity (*U*speed/*U*ref) by 7.60% and 1.20%, respectively. Overall, the presence of envelope features decreased on the wind speed components *u*, which were similar to those on the windward side. When balconies are present on the windward side, they can alter the wind speed and peak pressure (Stathopoulos and Zhu 1988; Montazeri and Blocken 2013; Yuan et al. 2018). The airflow did not have enough energy to enhance the average normalized horizontal velocity on the average normalized wind speed component (*u*/*U*ref) or the average normalized horizontal velocity (*U*speed/*U*ref) on the lateral side. Overhangs also enhanced the ventilation performance on the lateral side but were not as effective as they were on the windward side.

3.3 Analysis of the frequency of various force-dominated urban airflow patterns

Figure 11 shows the frequency of various force-dominated urban airflow patterns in multi-story buildings with different envelope features. On the windward side, three distinct flow states are observed: wind momentum dominance, wind momentum and thermal buoyancy dominance, and thermal buoyancy dominance. Notably, the frequency of wind momentum and thermal buoyancy dominance surpassed that of the other airflow patterns. When the presence of overhangs, the frequency of wind momentum dominance increased, while the frequency of wind momentum and thermal buoyancy dominance decreased compared to that of the flat-façade multi-story building. Conversely, in buildings with other envelope features, the frequency of wind momentum dominance decreased, while the frequency of wind momentum and thermal buoyancy dominance increased compared to that of a flat-façade multi-building. This indicates that the balconies, large wing walls, and small wing walls more easily led to wind momentum and thermal buoyancy dominating the airflow. On the lateral side, two distinct flow states are observed: wind momentum dominance and wind momentum and thermal buoyancy dominance. Notably, the frequency of wind momentum dominance surpassed that of other airflow patterns. Compared to a flat-façade multi-building, the frequency of wind momentum dominance increased in the overhang, large wing wall, and small wing wall multi-story buildings, while the frequency of wind momentum and thermal buoyancy dominance decreased. However, balconies increased the frequency of wind momentum and thermal buoyancy dominance and decreased the frequency of wind momentum dominance. Notably, the thermal buoyancy dominates airflow state can be observed in the multi-story building with overhangs on the windward side, and the multi-story building with large wing walls was also observed. However, these two situations for overhang and large wing walls developed for different reasons. For the multi-story building with overhang, although there were higher *U*ref values (e.g., ΔT = 2.43 °C, *T*ref = 26.44 °C, *U*ref = 0.193 m/s, and *Ri*b = 28.99),

the presence of the overhang created a greater temperature difference, which in turn led to *Ri*b ≥ 10 (the thermal buoyancy dominates airflow). For the multi-story building with large wing walls (e.g., ΔT =

0.87 °C, *T*ref = 26.43 °C, *U*ref = 0.138 m/s, and *Ri*b = 19.92), the large wing walls were less effective than the overhangs in creating a shading effect. However, the free flow velocity was lower, resulting in *Ri*b ≥ 10 (the thermal buoyancy dominates airflow). This indicates that a higher temperature difference and lower urban environmental wind speeds result in the thermal buoyancy effect dominating the urban airflow. Overall, the presence of overhangs enhanced the impact of wind momentum, increasing the frequency of wind momentum dominance on the windward and lateral sides. On the lateral side, except for the balconies, the envelope features increased the frequency of wind momentum dominance. The balconies reduce wall heat dissipation and enhance the thermal buoyancy effect on airflow, especially when located on the windward side. It is recommended to consider thermal buoyancy when analyzing how the envelope features affect wind-thermal environments, particularly in the cases of balconies.

3.4 Analysis of the air change per hour (ACH) in the multi-story building

Figure 12 shows the ACH in a multi-story building with different envelope features. For cross-ventilation, the presence of overhangs had less effect on the ACH value compared to the flat-façade multi-story building. However, the other envelope features reduced the ACH value in the following order of impact: large wing wall (69.98%) > small wing wall (25.79%) > balcony (12.12%). For single-sided ventilation on the leeward side, the presence of envelope features also decreased the ACH value. The order of impact is as follows: large wing wall (44.54%) > small wing wall (28.63%) > overhang (25.42%) > balcony (7.47%). For single-sided ventilation on the windward side, the presence of small wing walls increased the ACH value by 12.77% relative to the flat-façade multi-story building. However, the overhangs, balconies, and large wing walls decreased the ACH value by 39.34%, 20.07%, and 15.54%, respectively. The ACH values of single-sided ventilation on the windward side are better than that on the leeward side compared to the same envelope feature buildings, except the overhang building. The order of impact is as follows: small wing wall (92.43%) > large wing wall (75.69%) > flat-façade (22.01%)> balcony (11.25%). The overhangs had a similar impact on the single-side ventilation when they were present on the windward and lateral sides. Overall, cross-ventilation was more influenced by envelope features than single-sided ventilation. Large wing walls had the greatest impact on decreasing the ACH value than other envelope features. On the windward side, small wing walls raised the ACH value. But large wing walls had the opposite effect. Large wing walls increase turbulence but small wing walls can create a pressure difference and enhance natural ventilation. Therefore, small wing walls perform better than large wing walls in increasing the ACH value, even though both are vertical envelope features. Moreover, the presence of horizontal envelope features, such as overhangs, disrupted the downward or upward airflow and obstructed the flow, thereby reducing natural ventilation and decreasing the ACH value (Ai and Mak 2018; Cui et al. 2018; Cui et al. 2024b).

4 Limitations and future work

This study used scaled outdoor experiments to examine how envelope features affect indoor and outdoor ventilation performance in a multi-story building. However, many factors can affect the wind-thermal environment in urban. Future experiments should include various factors (i.e., various geometrical parameters, climate conditions, building types, building layouts, etc.) to reproduce realistic high-density city conditions (Hang et al. 2012; Palusci et al. 2022). Moreover, high-quality experimental data from this study may be utilized to conduct CFD simulation to validate theoretical models, further evaluating the thermal buoyancy in full-scale multi-story buildings (Chen et al. 2021b; Chen et al. 2023).

5 Conclusions

This research conducted scaled outdoor experiments in SOMUCH to examine the effect of various envelope features on outdoor ventilation, air change per hour (ACH), and airflow patterns in multi-story buildings. The primary conclusions are as follows:

1) Envelope features increased the average normalized wind speed component *u* (*u/U*ref). Notably, large wing walls led to a substantial increase of 21.61% in the average normalized wind speed component (*u/U*ref) on the windward side. Moreover, overhangs, small wing walls, and large wing walls contributed to increases in the average normalized horizontal velocity (*U*speed*/U*ref) of 12.41%, 10.56%, and 5.56%, respectively.
2) Cross-ventilation was more susceptible to envelope features than single-sided ventilation in air change per hour (ACH). Specifically, the ACH values of cross-ventilation for large wing wall, small wing wall, and balcony multi-buildings decreased by 69.98%, 25.79%, and 12.12% relative to the flat-façade building. Moreover, the ACH values of single-sided ventilation on the windward side are better than those on the leeward side, particularly the small wing walls led to a 92.43% increase in ACH values. However, the overhangs had a similar impact on the single-side ventilation of the windward and lateral sides.
3) The presence of overhangs improved wind momentum, increasing the frequency of wind momentum dominance on the windward and lateral sides. However, balconies slowed wall heat dissipation and enhanced the thermal buoyancy effect on urban airflow, particularly the presence of balconies on the windward side. Future work should include thermal buoyancy when examining the impacts of envelope features on the wind-thermal environment, particularly in the cases of balconies.
4) This study offers a valuable methodology for evaluating how envelope features affect ventilation performance in multi-story buildings. The conclusions can provide a valid basis for designing green building envelope features in high-density cities.

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