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Pedestrian level wind environment assessment around group of high-rise cross-shaped buildings: Effect of building shape, separation and orientation

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1. Introduction

Wind flow assessments around high-rise buildings, particularly in built-up areas in megacities, are essential for pollution dispersion and ensuring human health and thermal comfort at the pedestrian level [1–3]. Wind flow modeling in urban areas has recently received considerable attention due to an increase in urbanization and high-rise buildings, which directly affect wind flow patterns and urban environments [4]. Urban air quality is a major concern [1]. Dense areas have formed due to the blockage effect from high-rise buildings [5]. Outdoor wind comfort analyses are currently included in building design processes [6]. The majority of building design authorities worldwide recommend an outdoor wind comfort analysis prior to new building construction [6,7]. To estimate the wind-flow patterns around high-rise buildings within canopies and at the pedestrian level, various numerical techniques have been employed [8,9]. Due to advancements in modeling techniques, building parameters such as building orientations and separation are analyzed based on the wind flow characteristics in the respective area during the design stage. These parameters directly affect the wind flow patterns in the respective area, which alter the surrounding wind environment.

Numerous researchers have conducted outdoor investigations to create comfortable wind environments around buildings, especially at the pedestrian level. For example, Stathopoulos [10] examined all existing outdoor comfort criteria, especially wind speed, air temperature, and relative humidity, to ensure thermal comfort around various buildings. Blocken et al. [11] provided a comprehensive review of pedestrian-level wind environment assessments from 1960 onwards. With advancements in computational power, computational fluid dynamics (CFD) marked a breakthrough in wind engineering [12]. Blocken [8,12] discussed the detailed contributions of CFD in wind engineering over the last 50 years and provided guidelines for accurate CFD simulation. In addition to wind assessments, few researchers, such as Yang et al.
who described an approach to establishing a total comfort index, have focused on comfort criteria. Stathopoulos et al. [14] proposed pedestrian-level wind comfort criteria and discussed a knowledge-based approach to building design. Blocken et al. [15] proposed a modification to existing pedestrian-level wind assessment criteria. The majority of previous studies have been limited to wind flow analysis around conventional buildings. For irregularly shaped buildings, previous studies have been limited to wind load and pollution dispersion within the re-entrant bay [16,17]. Chow et al. [18] investigated wind flow through a re-entrant bay at a building’s midlevel. In a similar manner, Cheng et al. [19] examined pollution dispersion and flow through a re-entrant bay. Cook [20] provided an overview of wind flow in the re-entrant corner and bay of various arrangements; however, he did not provide details on wind flow patterns. In addition to wind comfort analysis, this study examines the influence of various wind incident directions and building separations on wind flow within the re-entrant corners of cross-shaped residential building blocks.

This study analyzed common cross-shaped residential building blocks, which are referred to as ‘harmony blocks’, in Hong Kong (Fig. 1). A ‘harmony block’ is a cross-shaped type of high-rise building block with 18 residential flats per floor. According to the Council on Tall Buildings and Urban Habitat, buildings taller than 50 m are referred to as high-rises [21]. Currently, harmony blocks are a mainstream, standard design for public rental housing in Hong Kong. Hong Kong is a densely populated city of more than 7 million people [22]. Compared with other Asian cities, Hong Kong has a unique urban morphology and humid weather. In 2003, the severe acute respiratory syndrome (SARS) virus spread in Hong Kong, which caused nearly 300 deaths. An investigation found that fatalities occurred in a high-rise cluster of buildings name “Amoy Garden”. More than 200 casualties were reported above the ninth floor of the buildings, whereas no casualties were reported below the ninth floor. After the investigation, medical professionals reported that the SARS virus may have originated in the 16th-floor bathroom of an infected unit and spread throughout the air-flow path of the building re-entrant bay to other units [23]. Mao et al. [24] recently discussed pollution dispersion and the transmission of infection among congested high-rise buildings in various locations. These incidents highlighted the importance of the orientations of re-entrant corners and bay for proper air ventilation. Studies have suggested that stagnant air reduces pollution dispersion and increases discomfort around buildings, which increases the risk of SARS-like events. Based on this brief review, the influence of wind incident directions on wind circulation within the re-entrant corners has not been established. Appropriate layout pattern and building orientation is very important for proper wind circulation and outdoor wind comfort [25,26]. In this study, a detailed investigation of wind circulation at the re-entranrs corners of cross-shaped buildings from various wind directions at the pedestrian level was performed. This study determines the optimum arrangement for a comfortable outdoor environment based on the wind circulation at the re-entrant corners. The remainder of the paper is organized as follows: Section 2 discusses a wind tunnel experiment, the numerical setup of the case study buildings, and the revised closure coefficients. The results of the case study building arrangements are presented in Section 3. Section 3 also details influence of the wind incident directions and passage width (building separation) on wind circulation and wind comfort. Section 4 presents the study’s conclusions.

2. Methodology

2.1. Experimental setup

For cross-shaped elements, an experiment was performed in a closed-circuit, subsonic boundary-layer wind tunnel facility at the City University of Hong Kong. The inside view, velocity sensor arrangements on the test board and the dimensions of the wind tunnel are shown in Fig. 2. The models were mounted on a circular table with a diameter of 2 m (Fig. 2(c)).

The schematic arrangements of the four tested configurations are shown in Fig. 3. The building models were fabricated at a scale of 1:280. The Hong Kong building department recommends a minimum building separation between high-rise buildings of 15 m for proper ventilation [28]. This study examines three building separations of 0.054 m, 0.107 m and 0.142 m (15 m, 30 m and 40 m, respectively, in full scale). The case study buildings are residential building blocks. Additional building separations (30 m and 40 m) were considered for greening and other recreational activities. However, this study only conducts a wind flow analysis. In three cases of building separation, the aspect ratio (H/W) was greater than two. The influence of various aspect ratios and flow regimes of the street canyon on flow parameters is well documented in Refs. [29,30]. An aspect ratio (H/W) > 2 is considered to be a deep street canyon [30]. In this study, however, buildings were distinctly arranged; in all cases, H/W > 2.

Fig. 4 shows all four scenarios, which are also listed in Table 1.

![Figure 1](image-url)

**Fig. 1.** Harmony blocks in an actual urban area and layout with wings locations [27].
Configuration 1 consists of eight building blocks, and configurations 2, 3 and 4 contain seven building blocks, five building blocks and three building blocks, respectively. The number of building blocks was reduced to investigate the blockage effect on wind circulation for various wind incident directions.

The small dot in Fig. 4 represents the velocity sensors positions. C1 to C16 depict the number of re-entrant corners. P1 to P4 indicate the passage number. The building scale dimensions S1, S2, and S3 were 0.048 m, 0.052 m and 0.057 m, respectively.

The building scale height (H) was 0.4 m. The buildings were distinguished by the letters A to E. The mean speed profile was fitted by a power law exponent of 0.15, which represents the open-exposure terrain. The normalized wind speed profile ($U/U_r$) and turbulent intensity profile ($I_u$) are shown in Fig. 5. The wind speed ($U$) was normalized using the reference wind speed ($U_r$) at a height of 1.8 m within a wind tunnel at a height 2 m. The velocity sensors...
were positioned at the pedestrian level at a height of approximately 0.007 m (2 m at full scale), as shown in Fig. 3. Due to the symmetrical arrangement of the building blocks, the velocity sensors were positioned halfway across a test board that measured 1 m × 1 m. In this study a Kanomax miniature L-shape velocity probe with a multichannel measuring system was employed (Kanomax USA). The precision of each sensor was ±3%. A hotwire anemometer was utilized for the inlet and approaching wind profile. For the wind tunnel scale, various wind assessment criteria are available. For example, Stathopoulos et al. [14] discussed a knowledge-based approach for a pedestrian-level wind comfort evaluation. The criterion by Stathopoulos et al. [14] is based on the wind speed ratio, which is referred to as the, “amplification factor” (Eq. (1)).

\[ k = \frac{U}{U_B} \]  

(1)

where k is the amplification factor (overspeed ratio), and U and U_B represent the wind velocity with the building at the same location and the wind velocity without the building at the same location, respectively. The amplification factor, which is based on the building scale, is defined in Ref. [14]. Ng [6] applied the normalized

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**Table 1**  
Test cases.

| Cases       | Building separation W (m) | Aspect ratio (\(λ = H/W\)) |
|-------------|---------------------------|-----------------------------|
| Configuration 1 | Case 1 0.054              | 7.45                        |
|             | Case 2 0.107              | 3.76                        |
|             | Case 3 0.142              | 2.84                        |
| Configuration 2 | Case 1 0.054              | 7.45                        |
|             | Case 2 0.107              | 3.76                        |
|             | Case 3 0.142              | 2.84                        |
| Configuration 3 | Case 1 0.054              | 7.45                        |
|             | Case 2 0.107              | 3.76                        |
|             | Case 3 0.142              | 2.84                        |
| Configuration 4 | Case 1 0.054              | 7.45                        |
|             | Case 2 0.107              | 3.76                        |
|             | Case 3 0.142              | 2.84                        |

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**Fig. 4.** Building configurations, location of re-entrant corners (C1–C16), and building passages (P1–P4).

**Fig. 5.** Inflow normalized wind speed (U/U_r) and turbulent intensity (I_u) profiles.
wind speed to evaluate the wind environment at the pedestrian level and proposed pedestrian-level wind assessment guidelines for a case study area in Hong Kong. Ng [6] indicated that a wind speed of 1.0–1.5 m/s is required at the pedestrian level (height of 2 m) for a comfortable environment around buildings. In Hong Kong, the Hong Kong Observatory provides the mean wind speed and direction. An annual mean wind speed of 3.1 m/s at a height of 90 m and a prevailing wind direction of east-southeast are observed throughout the year (Hong Kong Observatory). According to the Hong Kong Observatory, the mean wind speed is 6–8 m/s at a height of 500 m [6]. Therefore, a normalized wind speed (NWS) range of approximately 0.25–0.3 is required for a comfortable environment in relation to this height [6]. Ng [6] indicated a wind speed ratio of 0.3 in open spaces in Hong Kong. This study considered the wind assessment criteria discussed by Ng [6] to evaluate a pedestrian-level wind environment. The reference wind velocity within the wind tunnel was set to 10 m/s at a height of 1.8 m for the wind tunnel. A neutral boundary layer profile that was characterized by the power law exponent of 0.15 was constructed [31]. The roughness length was set to 0.013 m in the experiment and simulation [31]. The wind velocity at the pedestrian level was normalized using the reference wind speed. Based on the Ng [6] study, three NWS limits were defined for the wind flow assessment in this study. Table 2 lists the three NWS regions that were defined for the case study analysis.

This study evaluated pedestrian-level wind flow regions around the case study arrangements and within the re-entrant corners using the criteria listed in Table 2. For simplicity, all cases were defined (building separation cases 1–3 [Table 1] – building configurations 1–4 [Fig. 4] – wind incident direction [3]). For example, Case 1-2-22.5° indicates building separation Case 1, Configuration 2, and a wind incident direction of 22.5°.

### 2.2. Numerical approach

Many numerical techniques, such as Reynolds-averaged Navier–Stokes (RANS) turbulence models, large eddy simulation (LES), and direct numerical simulation (DNS) techniques, are currently available [8,32]. Although LES and DNS are more accurate, these techniques are rarely employed and unpopular for urban wind assessments and airflow analysis due to high computational costs and difficulties in tuning [33,34]. In addition, Janssen et al. [34] indicated that LES is ideal for wind flow assessment, whereas simulations are typically performed from numerous wind directions (e.g., 12 or 16) for pedestrian-level wind flow analysis. Therefore, RANS steady analysis is preferred to transient analysis for wind flow assessment due to the high computational cost of transient analysis [33,34]. Based on this brief review, the standard k–ε (SKE) turbulence model with revised closure coefficients was selected for this study. The current forms of the k–ε model, which comprise “the SKE turbulence model”, were developed by Launder and Spalding [35]. The model transport equations for k and ε are [36].

\[
\begin{align*}
\frac{\partial k}{\partial t} + \rho U \frac{\partial k}{\partial x_j} &= \left( \mu + \frac{\nu_k}{C_1} \right) \frac{\partial}{\partial x_j} \left( \frac{\partial k}{\partial x_j} \right) + \frac{\nu_k}{C_1} \frac{\partial}{\partial x_j} \left( \frac{\partial U}{\partial x_j} \right) - \rho \varepsilon \quad (2)
\end{align*}
\]

\[
\begin{align*}
\frac{\partial \varepsilon}{\partial t} + \rho U \frac{\partial \varepsilon}{\partial x_j} &= \left( \mu + \frac{\nu_k}{C_1} \right) \frac{\partial}{\partial x_j} \left( \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{C_m}{k} \frac{\partial U}{\partial x_j} \frac{\partial U}{\partial x_j} - C_{\varepsilon} \frac{\varepsilon}{k} \frac{\partial \varepsilon}{\partial x_j} 
\end{align*}
\]

The SKE model involves various damping functions and closure coefficients. Damping functions are required for an accurate prediction of the near wall flow, and closure coefficients are calibrated using experimental data that are based on simple flow configurations and are fixed using computer optimization. Current “standard” values of closure coefficients in the SKE turbulence model were defined by Launder et al. [37]. A universal set of closure coefficients is unavailable. Various studies have reported that the closure coefficient may require fine-tuning for accurate results [38,39]. In this study, the fine-tuning of closure coefficients was performed. Details are provided in the next subsection.

#### 2.2.1. Revised closure coefficients

In turbulence closure models, closure coefficients are required for parameterizing the flow field and accurately modeling conditions. With advancements in CFD, various new models have been developed, such as the RNG k–ε turbulence model by Yakhot et al. [40], and the Realizable k–ε turbulence model by Shih et al. [41]. Instead of developing novel models, certain researchers have attempted to modify the closure coefficients of the original SKE turbulence model. For instance, Richards et al. [42] proposed a set of closure coefficients for ABL simulations that were based on field measurement data. In a similar manner, Panofsky et al. [43] proposed closure coefficients for wind flow over a flat terrain. In addition, Detering et al. [44] and Beljaars et al. [45] have proposed modified closure coefficients for ABL modeling. Although these coefficients differ in numerous aspects, the purpose of the modifications was to reduce uncertainties in the quantities of interest. For additional details regarding the different models and closure coefficients, please refer to [46]. The majority of recently modified closure coefficients have been developed to serve specific needs and particular flow conditions. In this study, revised closure coefficients were applied for pedestrian-level wind flow analysis. Revised closure coefficients were based on recommendations by Guillas et al. [38].

Guillas et al. [38] performed Bayesian calibration and recommended a set of closure coefficients for street canyon wind flow analysis (Table 3). In this study, the set of closure coefficients that were suggested by Guillas et al. [38] was tuned for the problem being analyzed. From the set recommended by Guillas et al. [38], two test ranges were evaluated, as shown in Table 3. Guilles et al. [38] and Edeling et al. [39] have indicated that the lower values of σk (0.53 and 0.462) and σε (0.5 and 0.42) significantly improve the performance of the SKE turbulence model. In this study, C2 and C3

| Table 3 | Test range and revised closure coefficients. |
|---------|----------------------------------|
| Cρ     | C1     | C2     | σε     | σk     |
| Standard values | 0.09 | 1.44 | 1.92 | 1.3 | 1.0 |
| Guillas et al. [38] | 0.12 | 1 | 1.2 | Lower values |
| Test range-I | 0.09–0.12 | Eq. (4) | 1.92 | 0.5 | 0.53 |
| Test range-II | 0.09–0.12 | Eq. (4) | 0.5 | 0.53 |
| Revised values | 0.12 | 1 | 1.92 | 0.5 | 0.53 |
were evaluated using fixed values of $\sigma_k$ and $\sigma_\epsilon$, as recommended by Guillas et al. [38]. Equation (4), which was defined by Richards et al. [42], was used to calculate $C_1$ and $C_2$ in test ranges I and II, respectively. The modifications of the closure coefficients necessitate a precise evaluation based on experimental results. In this study, the simulation results were evaluated by conducting the wind tunnel experiment.

$$\sigma_\epsilon = \frac{k^2}{(C_2 - C_1) \sqrt{C_u}}$$  \hspace{1cm} (4)

where $k$ is the von Karman constant. After running simulations involving various combinations, a set of closure coefficients was selected (Table 3).

To evaluate the selected range of closure coefficients, the wind flow through the passages in Configuration 1 (Fig. 4) was considered. Fig. 6 shows the results of Test Range 1. The standard value of $C_2$ and the value revised by Guillas et al. [38] were determined to have a nonsignificant difference. Both Test Ranges 1 and II yielded similar results. Therefore, $C_2$ was maintained as the standard value due to its strong correlation with other parameters. In addition, $C_1$ and $C_2$ were employed to control the spreading rate of the mixing layer, which was crucial for the logarithmic layer [47]; the fine-tuned revised values were subsequently selected (Table 3). A detailed discussion on the closure coefficient is beyond the scope of this paper; for additional details, please refer to [46,47].

2.2.2. Computational domain and boundary conditions

The dimensions of the computational domain and boundary conditions were set in accordance with the Architectural Institute of Japan (AIJ) guidelines for pedestrian-level wind flow analysis (Fig. 7(a)) [48]. The inlet boundary conditions were based on the wind tunnel experiment. The turbulent kinetic energy (TKE) was calculated using the turbulent intensity ($I_t$) relation—$k = 0.5 (I_t U)^2$—and the inflow wind velocity ($U$) [49]. The turbulent dissipation rate ($\epsilon$) of TKE was based on the local equilibrium ($P_\kappa = \epsilon$) = $C_\kappa k^1/2$ [49], where $l = C_{\kappa}^{1/4} k^{1/2}(dU/dz)^{-1}$. The standard wall function was applied for the building wall and ground surface. The sand grain-based roughness modification ($k_r$-type) was employed for the ground surface [50], of which the parameters $k_0 = 0.18$ and $C_0 = 0.7$ were determined using the roughness length $z_0 = 0.013 \text{ m}$. The building surface was considered to be smooth. Symmetry boundary conditions were imposed on the upper and lateral surfaces of the domain. The zero gradient condition was applied at the outlet. Various wind incident directions were set with the ICEM CFD tool using the advance multiblock structured grid generation technique for symmetrical objects. The block rotation tool was employed to rotate the inner block (Block 1) prior to grid generation. After establishing the required orientation, the multiblock-structured grid was generated for all blocks (for additional details, refer to ref. [51]). Three block orientations were applied to cover all wind incident directions. The grids were generated stepwise; initially, each orientation building arrangement was set at the required orientation, after which the multiblock and grids were generated. Fig. 7(b) shows the grid arrangement, and Fig. 7(c) shows the positions for the wind incident directions of 0°, 90°, 180°, and 270°. Fig. 7(d) shows the grid positions for 22.5°, 67.5°, 112.5°, 157.5°, and 247.5°. Fig. 7(e) shows the grid positions for 45°, 135°, 225°, and 315°. According to Snyder [52], a Reynolds number greater than 4000 is required to achieve Reynolds number (Re) independency. In this study, Reynolds number independency was achieved with a Re of 1.1 × 10^5 according to the building width (H) and wind velocity at $z = H$, which is considerably larger than 4000. To maintain high accuracy, 3D steady RANS equations were solved with double precision using the simulation code Fluent. Among CFD simulation codes, Fluent is commonly employed in building physics for wind flow analysis [8,32]. A second-ordered discretization scheme for all convection and diffusion terms, and the SIMPLE algorithm was employed for pressure–velocity coupling. Convergence was carefully monitored, and a solution was obtained at a convergence level of 10^-4 for continuity and TKE terms and at a convergence level of 10^-6 for all other terms.

2.2.3. Grid-independent study

A grid-independent analysis was performed by constructing three sets of hexahedral-based structured grids, as described in previous studies [8,53]. The coarse grid had approximately 766,262 hexahedral cells, and the basic grid had 1,637,020 hexahedral cells. A grid refinement ratio of 2.0 was employed to refine the grids. The finer grid had 3,212,879 hexahedral cells. Grid sensitivity analysis was performed in two steps. In Step 1, the NWS ($U_{\text{WS}}$) of the basic grid was compared against the coarse and fine grids (Fig. 8). Fig. 8 shows that a smaller difference in NWS was obtained for basic and fine grids than basic and coarse grids. The figure also shows that the performance with the basic grid was superior in terms of accuracy and computational cost. In Step 2, the grid convergence index (GCI) (Eq. (5)), which is based on the Richardson extrapolation [54] proposed by Roache [55], was calculated to ensure grid accuracy.

$$\text{GCI} = F_r \frac{\epsilon_{\text{rms}}}{p^r - 1}$$  \hspace{1cm} (5)

Table 4 lists the major GCI parameters. The root-mean-square relative error ($\epsilon_{\text{rms}}$) was calculated using Eq. (6).

$$\epsilon_{\text{rms}} = \left( \frac{\sum_{i=1}^{n} a_i^2}{n} \right)^{1/2}$$  \hspace{1cm} (6)

where $F_r = 1.25$ is the safety factor, $r = 2$ represents the grid refinement ratio, $n$ is the number of measuring points, and $p = 2$ is based on the second-order discretization of all terms.

The GCI has no fixed value; however, various researchers, such as Vinchurkar et al. [56] who indicated that the GCI should be maintained at less than 5% to ensure grid accuracy, have recommended a lower value. As shown in Table 4, the GCI is less than 5% in both sets of grids. Based on the aforementioned grid-independent study, the basic grid was selected for the case-study analysis.
3. Results and discussion

As mentioned in Section 2, the aspect ratio in all cases was greater than 2, for which appropriate natural ventilation is required at the pedestrian level. In the case-study arrangements, the frontal area density varied from 0.06 to 0.18. A detailed discussion is provided in the following subsections.

3.1. Wind flow variations at re-entrant corners

In this subsection, wind flow at the re-entrant corners of the case-study building configurations with three passage widths (Building separations) was investigated from various wind directions. The NWS (Table 2) was employed for the wind flow assessments within the re-entrant corners.
3.1.1. Configuration 1

Fig. 9 shows the variations in NWS at the re-entrant corners of Configuration 1 for the experiment (Exp.) and the numerical simulation (Sim). In Configuration 1, five wind directions and 16 re-entrants corners were investigated. In Fig. 9, the wind direction at $\alpha = 0^\circ$ was normal in relation to the building arrangement. The NWS at C1, C3 and C4 was high compared with C2, C5 and C6, respectively, due to the downward wake of buildings A and B. At C7, the NWS was high due to the venturi effect of P1; in a similar manner, the high NWS at C4 was due to the aerodynamic effect of the building corners. The NWS from C9 to C16 decreased compared with C1 to C8 due to the building wake and drag losses. At $\alpha = 0^\circ$, the re-entrant corners at the leeward side were inherently covered within the wake region of the buildings; therefore, the magnitude of the NWS in these corners was reduced. In Case 2-1-0, a similar behavior of wind flow was observed at the re-entrant corners, with the exception of a slight reduction in wind speed due to a reduction in the venturi effect of passages.

In Case 3, fewer re-entrant corners were observed in a low wind speed region due to a reduction in $\lambda$ and passage drag. At $\alpha = 22.5^\circ$, the behavior of the NWS was relatively similar to the behavior of the NWS at $\alpha = 0^\circ$. At $\alpha = 22.5^\circ$, the NWS at the outward re-entrant corners (e.g., C4, C8 and C12) slightly increased and decreased at the re-entrant corners that lay inward to the building arrangement (e.g., C7, C10 and C11). In all three cases (Table 5), $\alpha = 45^\circ$ yielded an improved ventilation potential, and the majority of the re-entrant corners had an acceptable NWS. At $\alpha = 45^\circ$ and $67.5^\circ$, the results revealed a similar flow rate within the re-entrant corners. The

| Grids     | $\varepsilon_{rms}$ (%) | GCI (%) |
|-----------|-------------------------|---------|
| Grid I–II | 5.5                     | 2.29    |
| Grid II–III | 4.3            | 1.79    |

Fig. 8. Comparison of NWS ($\frac{U}{U_r}$) of coarse and basic grids and fine and basic grids at $x = -1.0$. 

Fig. 9. NWS at re-entrant corners (C1–C16) of Configuration 1.
aspect ratio significantly affected the NWS of the re-entrant corners. At $\alpha = 45^\circ$, the NWS at C6 in Cases 1 to 3 varied from 0.105 to 0.191 (45% increased), respectively. In a similar manner, the NWS in C10 varied from 0.11 to 0.264 (58% increased), and the NWS in C15 varied from 0.075 to 0.111 (32% increased). In C10, the NWS was significant due to the venturi effect of the passage. Similar behaviors were observed in other re-entrant corners at various wind directions. A low NWS at the re-entrant corners indicated the presence of a stable vortex at the re-entrant corners. A wind incident angle range of $22.5^\circ < \alpha < 67.5^\circ$ significantly improved the ventilation potential within the re-entrant corners. Table 5 compares the wind flow within the re-entrant corners in the three NWS regions (L, A, and H) regarding the number of sensors for the experiment (E) and numerical simulation (S). A small difference in high wind speed regions as detected in the numerical simulation and experiment results. However, the difference in high and acceptable wind velocities was not as prominent. The NWS variation trend in the simulation was similar to the NWS variation trend in the experiment results. Fig. 9 displays the mean absolute error (MAE) between the NWS of the experiment and the NWS of the numerical simulation. The average NWS in Configuration 1 from all wind directions ranged from 0.082 to 0.346. In Case 3, at $\alpha = 22.5^\circ$, the MAE was higher than the MAE at other wind incident angles. However, the MAEs in all cases of Configuration 1 were below 0.06 and varied from 0.01 to 0.06.

3.1.2. Configuration 2

In configuration 2, the buildings were arranged in a U-shape. In this configuration, wind flow in 14 re-entrant corners and nine wind directions were examined. Fig. 10 shows the NWS for both the experiment and the numerical simulation. At $\alpha = 0^\circ$, a slight increase in NWS was observed due to the elimination of building A (Configuration 1). At $\alpha = 45^\circ$ and $135^\circ$, fewer re-entrant corners are located inside the low wind speed range. At $\alpha = 45^\circ$, the NWS at C4 varied in Cases 1 to 3 from 0.113 to 0.242 (53% increase), respectively. In a similar manner, in C8, the NWS varied from 0.126 to 0.234 (46% increase), and in C13, the NWS varied from 0.072 to 0.115 (37% increase). In C8, the NWS increase was less than the NWS increase with C10 in configuration 1 due to the open side and the absence of a venturi effect from this side. Similar behaviors were observed in other re-entrant corners at various wind directions. Based on an acceptable NWS, $\alpha = 157.5^\circ$ exhibited improved ventilation potential within the re-entrant corners in all three cases. At $\alpha = 0^\circ$, $90^\circ$ and $180^\circ$, the majority of the re-entrant corners were located within the downward wake region of the buildings and had a low NWS. With an increase in wind incident angle, the position of the wake region changed, and the low NWS regions also shifted with the wind incident directions. Due to the variations in the wake region, the flow within the re-entrant corners also changed. In all three cases of Configuration 2, the wind incident ranges $22.5^\circ < \alpha < 67.5^\circ$ and $135^\circ < \alpha < 157.5^\circ$ improved the considerable ventilation potential at the re-entrant corners. The MAE was estimated by comparing the experimental and simulation results. The average NWS in all cases of Configuration 2 varied from 0.121 to 0.233. In all cases, the MAE was less than 0.06. At $\alpha = 135^\circ$ and $180^\circ$, the MAE increased to 0.058 and 0.05, respectively. Table 6 lists the number of re-entrant corners within different NWS regions. Compared with the re-entrant corners in the experiment results, a low number of high wind speed corners were detected in the simulation results. However, the difference in wind speed was dissimilar to the difference in wind speed in Configuration 1.

3.1.3. Configuration 3

In configuration 3, the buildings were arranged in an L-shape. Eleven wind incident directions and wind flow at 14 re-entrants corners were investigated. With this arrangement, the NWS within the re-entrant corners significantly improved compared with Configurations 1 and 2. With this arrangement, the majority of the buildings were subjected to direct wind flow due to the open sides and reduction in the wind catching effect at the re-entrant corners. Fig. 11 displays the NWS, and Table 7 lists the number of sensors at the re-entrant corners that are located within the three NWS regions in the experiment (E) and numerical simulation (S). The variation trend in wind speed regions was similar to the variation trend in the wind speed regions in Configurations 1 and 2.

In Case 1, $\alpha = 0^\circ$, 135$^\circ$ and 157.5$^\circ$ yielded improved results. In Case 2, $\alpha = 45^\circ$, 67.5$^\circ$ and 135$^\circ$ yielded better results. Similarly, in Case 3, $\alpha = 67.5^\circ$ and 247.5$^\circ$ significantly improved the ventilation potential. At $\alpha = 135^\circ$, the NWS at C1 in Cases 1 to 3 varied from 0.116 to 0.314 (63% increase), respectively. In C5, the NWS varied from 0.115 to 0.314 (63.3% increase), and in C14, the NWS varied from 0.84 to 0.151 (44% increase). In an identical manner, the NWS varied with the wind incident directions in other re-entrant corners with variations in building separation. In Configuration 3, the average NWS varied from 0.11 to 0.235. The MAE in all cases varied from 0.01 to 0.06, which was similar to the outcomes for Configurations 1 and 2. However, in Configuration 3, the total MAE was lower than the MAE in Configurations 1, 2 and 4.

3.1.4. Configuration 4

Fig. 12 and Table 8 show the results of Configuration 4. In this configuration, 12 re-entrant corners and five wind incident directions were examined. With this arrangement, the re-entrant corners at the windward side had a slightly higher NWS compared with other configurations. Similarly, at $\alpha = 22.5^\circ$, the NWS at C4, C8 and C12 in Cases 1 to 3 increased 63.94%, 69.06% and 60.90%, respectively. The trend in NWS variations from $\alpha = 0^\circ$ to $90^\circ$ was relatively similar to other configurations, with the exception of a minor difference in NWS that was attributed to the building arrangements observed with a normal wind direction. In this arrangement, the wind incident range $22.5^\circ < \alpha < 67.5^\circ$ exhibited an improved ventilation potential. In Case 3 of Configuration 4, the NWS was lower than the NWS in the experimental results at a few re-entrant corners. In all cases of Configuration 4, the average NWS
ranged from 0.105 to 0.229. In addition, the MAE of all wind incidence angles varied between 0.02 and 0.082, which exceeded the MAE values of Configurations 1, 2, and 3.

In all configurations, the majority of the re-entrant corners were covered within the downward wake region with normal wind directions and exhibited poor ventilation potential. Stable vortices were observed with normal wind directions at the re-entrant corners downstream of the buildings. At skewed wind directions, the wind flow within the re-entrant corners improved due to an increase in swirl flow at the corners and a reduction in the sheltering effect in the adjacent buildings. The swirl flow drove the wind in the stagnant area, and the vortices moved outward and improved the wind environment. This type of flow is essential for removing contaminants from the stagnant area of re-entrant corners in the vicinity of high-rise buildings.

### 3.2. Building orientation and wind comfort

To quantify the influence of wind incident direction and building separation on wind comfort, 90 cases were evaluated by

![Fig. 10. NWS at re-entrant corners (C1–C14) of Configuration 2.](image-url)

#### Table 6

| Case 1 (α) | No of sensors | Case 2 (α) | No of sensors | Case 3 (α) | No of sensors |
|------------|---------------|------------|---------------|------------|---------------|
| L          | A             | H          | L             | A           | H             |
| E          | S             | E          | S             | E          | S             |
| 0°         | 4 4 10 10    | 0 0        | 0             | 4 5 10 9   | 0 0           |
| 22.5°      | 4 5 9 9      | 1 0        | 22.5°         | 5 6 9 8    | 0 0           |
| 45°        | 1 1 11 13    | 2 0        | 45°           | 0 1 13 13  | 1 0           |
| 67.5°      | 2 3 10 11    | 2 0        | 67.5°         | 2 3 11 11  | 1 0           |
| 90°        | 6 5 6 9      | 2 0        | 90°           | 5 5 9 9    | 0 0           |
| 112.5°     | 3 4 10 10    | 1 0        | 112.5°        | 2 2 11 12  | 1 0           |
| 135°       | 1 0 10 14    | 3 0        | 135°          | 1 1 11 13  | 2 0           |
| 157.5°     | 3 4 11 14    | 0 0        | 157.5°        | 2 1 12 13  | 0 0           |
| 180°       | 6 7 7 6      | 1 1        | 180°          | 7 7 7 7    | 0 0           |
| 22°        | 4 3 9 11     | 1 0        | 22°           | 3 3 11 11  | 0 0           |
| 45°        | 1 3 13 11    | 0 0        | 45°           | 1 3 13 11  | 0 0           |
| 67.5°      | 2 4 12 10    | 0 0        | 67.5°         | 2 4 12 10  | 0 0           |
| 90°        | 5 5 9 9      | 0 0        | 90°           | 5 5 9 9    | 0 0           |
| 112.5°     | 2 2 11 12    | 1 0        | 112.5°        | 2 2 11 12  | 1 0           |
| 135°       | 1 1 9 13     | 4 0        | 135°          | 1 1 9 13   | 4 0           |
| 157.5°     | 2 2 11 12    | 1 0        | 157.5°        | 2 2 11 12  | 1 0           |
| 180°       | 4 3 10 11    | 0 0        | 180°          | 4 3 10 11  | 0 0           |
conducting wind tunnel experiments and numerical simulations. This section presents a detailed discussion of all cases. Due to space limitations, only the contours of the selected cases are presented in the figures; all other cases are summarized in the tables. Sixty velocity sensors were employed in configurations 1, 2 and 3, and 48 velocity sensors were employed in configuration 4 to evaluate the pedestrian-level wind environment around various building arrangements. Wind comfort criteria, as described in Section 2 (Table 2), were considered for the evaluation of the pedestrian-level wind environment, which indicate the wind comfort level for pedestrians at a particular wind direction and location. Each sensor covered a specific area, and additional sensors enable more areas to be covered within a specific wind region (L, A and H).

3.2.1. Configuration 1

Table 9 lists the number of sensors for Configuration 1. Five prevailing wind directions were considered for Configuration 1. Table 9 indicates that the low wind area decreased as the wind incident angle increased from 0° to 45° and subsequently increased from 45° to 90°. At 45°, a greater area was covered with an acceptable NWS. In Cases 2 and 3, the wind circulation improved due to a reduction in λ. In Case 3, at α = 45°, a zero low wind region was detected. Fig. 13 shows the contour of the NWS for Case 1-1-45° and Case 2-1-67.5°. At α = 0°, the approaching wind was normal considering the building arrangement. Building C and Building D were covered within the downward wake of Building A and Building C, respectively. Building E was unaffected by the wake.
region; however, the wind velocity was lost due to the drag of the buildings located upstream. In Case 1-1-45°, the NWS at all passages was similar due to the equal wind incident angle with respect to the passages. In Case 2-1-67.5°, Passages 1 and 4 faced less wind due to a greater wind angle (67.5°), whereas Passages 2 and 3 had more wind due to a lower (22.5°) wind angle. Table 9 reveals that the acceptable NWS range area increased in Case 3 of Configuration 1; however, a high wind speed area also increased compared with Cases 1 and 2. The flow pattern, vortex formation and wake area caused by upstream building drag was redistributed in each wind incident direction. With variations in these parameters, the wind speed regions L, A and H also varied. In Case 1-1-45° and Case 2-1-
67.5°, a smaller low wind speed area was observed. In Case 1-1-45°, however, building D was affected by the wake of building B. Conversely, less building interference and the mutual sheltering effect were observed in Case 2-1-67.5° due to the low H/W.

Fig. 13 shows the contour of the selected cases of Configuration 1 based on the results of the wind tunnel experiment and simulation.

### 3.2.2. Configuration 2

Table 10 summarizes the data of the wind speed sensors from the experiment and numerical simulation of Configuration 2. In Configuration 2, wind comfort was evaluated at nine wind directions. In Configuration 2, the low wind speed area decreased as α increased from 0° to 45° and 90°−135°. In a similar manner, the low wind speed area increased from 45° to 90° and 135°−180°. The acceptable wind speed area was large in Cases 1-2-22.5°, 1-2-45° and 1-2-157.5° (Fig. 14). In Case 2-2-45°, no sensor was detected in the low-speed region. In Cases 3-2-22.5° and 3-2-67.5°, more sensors were located in the acceptable range. Fig. 14 shows the

### Table 10

| Case 1 (α) | No of sensors | Case 2 (α) | No of sensors | Case 3 (α) | No of sensors |
|------------|---------------|------------|---------------|------------|---------------|
| L          | A             | H          | L             | A           | H             |
| E          | S             | E          | S             | E          | S             |
| 0°         | 9             | 10          | 29            | 29          | 10            | 9             | 0°             | 9             | 8             | 42            | 43            | 9             | 9             | 22.5°         | 3             | 3             | 45            | 45            | 12            | 12            |
| 22.5°      | 7             | 8           | 30            | 29          | 11            | 11            | 22.5°         | 1             | 2             | 44            | 44            | 15            | 14            | 45°           | 1             | 2             | 44            | 44            | 15            | 14            |
| 45°        | 1             | 3           | 37            | 37          | 10            | 8             | 45°           | 1             | 2             | 44            | 44            | 15            | 14            | 67.5°         | 1             | 0             | 45            | 44            | 14            | 14            |
| 67.5°      | 2             | 3           | 31            | 32          | 15            | 13            | 67.5°         | 0             | 1             | 42            | 44            | 17            | 16            | 90°           | 5             | 3             | 40            | 43            | 15            | 14            |
| 90°        | 6             | 6           | 25            | 27          | 17            | 15            | 90°           | 5             | 3             | 40            | 42            | 15            | 15            | 22.5°         | 0             | 0             | 40            | 41            | 20            | 19            |

Fig. 13. Contour of NWS of different cases of Configuration 1 at the pedestrian level in the (a) numerical simulation and (b) wind tunnel experiment.
contour of the NWS of Cases 1–2–157.5°, 2–2–45°, 2–2–135° and 3–2–22.5°. In Case 1–2–157.5°, a high NWS was obtained at the passages and upstream edges (e.g., at building C). In Case 2–2–45°, the NWS distribution was more suitable compared with the other cases. In a similar manner, in Case 3–2–22.5°, buildings B, C and D were covered in the downward wake and faced the upstream building drag, which caused a reduced NWS around the buildings. In Case 3–2–67.5°, a high NWS was obtained near the wall within the passages, as in Case 1–2–157.5°. Stable vortices were also observed downstream of all cases in normal wind directions.

### 3.2.3. Configuration 3

Configuration 3 was evaluated from 11 wind directions. Table 11 lists the wind speed sensors. In this configuration, Cases 1–3–157.5°, 2–3–0°, 2–3–135° and 3–3–67.5° had suitable wind conditions around the buildings. Fig. 15 shows a contour plot for the selected

| Case 1 (σ) | No of sensors | Case 2 (σ) | No of sensors | Case 3 (σ) | No of sensors |
|-----------|---------------|-----------|---------------|-----------|---------------|
| L A H     | L A H         | L A H     | L A H         |
| 0°        | 4 4 30 14 14 | 4 5 38 18 18 | 6 5 41 13 12 |
| 22.5°     | 4 5 33 11 10 | 22.5°     | 5 6 40 14 14 | 4 4 45 11 11 |
| 45°       | 1 1 35 12 12 | 45°       | 0 1 45 15 14 | 45°       |
| 67.5°     | 2 3 33 14 12 | 67.5°     | 2 3 39 19 18 | 67.5°     |
| 90°       | 6 5 26 19 17 | 90°       | 5 5 40 15 15 | 90°       |
| 112.5°    | 4 5 31 13 12 | 112.5°    | 4 4 39 17 16 | 112.5°    |
| 135°      | 1 0 36 15 12 | 135°      | 1 1 39 22 20 | 135°      |
| 157.5°    | 3 4 37 11 11 | 157.5°    | 2 1 39 19 19 | 157.5°    |
| 180°      | 8 9 29 10 10 | 180°      | 7 7 43 10 10 | 180°      |

**Fig. 14.** Contour of NWS of different cases of Configuration 2 at the pedestrian level in the (a) numerical simulation and (b) wind tunnel experiment.
cases. In Case 2-3-0°, due to the aerodynamic effect of the corners of building D, the wind flow toward P2 counteracted the downward wake effect of building B. In Case 2-3-135°, all passages had a similar NWS, and a high-speed zone was detected near the building corners. At α = 67.5°, the high wind speed area was large, and a high wind speed was obtained in the passage corners due to the absence of the buildings downstream. In this configuration, wind incident angles of 67.5° and 135° improved the wind conditions.

3.2.4. Configuration 4

In Configuration 4, the buildings were arranged in a line. The wind flow behavior in Configuration 4 was relatively similar to the wind flow behavior in Configuration 1. However, the NWS around the buildings was high in this configuration due to the absence of
downstream buildings. With this arrangement, wind incident angles of 45° and 67.5° provided a suitable wind environment around the buildings. At wind incident angles of 22.5°−45°, the building sheltered effect was low in all cases. In all other wind incident directions, the influence of the buildings upstream on the buildings downstream was observed. In all normal wind directions, worse wind conditions were observed for pedestrians. At the passage corners of the buildings or near the corners, a high NWS was observed in normal wind directions. Table 12 lists the wind speed sensors. Fig. 16 shows the contour of the selected cases of Configurations 4, which are based on the results of the wind tunnel experiment and numerical simulation.

The percentage of the covered area of the three wind speed regions for all configurations and the average wind speed area (Ave.) of all configurations are summarized in Tables 13–16. In Configuration 1 (Table 13), at $\lambda = 3.76$ and 2.84 with $\alpha = 0°$–67.5° in both cases, more than 70% of the area fell within an acceptable wind speed region. At 45°, however, the size of the acceptable wind speed area decreased with the aspect ratio due to the symmetrical arrangement that created a wake region and reduced the wind circulation at the leeward side of the building arrangement. Similarly, in Configuration 2 (Table 14), at $\lambda = 2.84$ with $\alpha = 0°$–67.5°, a larger acceptable wind speed area was observed compared with the acceptable wind speed area observed for the other wind incident angles. From 90° to 157.5°, at $\lambda = 7.45$, the size of the acceptable wind speed area increased; however, minimal differences were observed at $\lambda = 3.76$ and 2.84.

In Configuration 3 (Table 15), with the decreased aspect ratio, the acceptable wind speed area increased by 2%–5%. This increase was attributed to a larger amount of open space, which enabled the wind to freely circulate compared with the conditions of Configurations 1 and 2. Similarly, in Configuration 4 (Table 16), at $\alpha = 0°$ and 67.5°, improved results were observed at a lower aspect ratio. All other wind incident angles in Cases 2 and 3 produced similar results.

4. Conclusions

This study investigated the wind circulation within re-entrant corners and wind comfort around various building configurations from various wind directions. The findings revealed the importance of the wind incident direction for wind circulation within the re-entrant corners of closely constructed high-rise buildings. Based on the aforementioned analysis, significant variations in normalized wind speed at re-entrant corners were observed in various building arrangements. Four building configurations (square-, U-, L- and I-shape) were investigated from various wind incident directions and with different levels of building separation or aspect ratios. The results indicated that wind circulation within the re-entrant corners were significantly affected by the wind incident direction and building separations. On the windward side, the difference in the normalized wind speed in the various configurations was reduced due to similar wind incident conditions and flow patterns. However, a major difference was observed on the downstream side due to variations in flow patterns, blockage effect, and building arrangements. At wind incident angles that range from 0° to 90°, a 40% increase in normalized wind speed was observed for the square-shaped building arrangement. Similarly, in U-shaped building arrangements, wind incident angles that ranged from 0° to 180° yielded a 46.6% increase in normalized wind speed. In L- and I-shaped arrangements, increments of 50.36% and 45%, respectively, in normalized wind speed were recorded on the leeward sides of buildings. The aforementioned analysis illustrates that the L-shaped building configuration exhibited the highest wind circulation at the re-entrant corners, which directly improved the ventilation potential compared with other building configurations.

At the wind incident angle range from 22.5° to 67.5° and at 135°, the wind circulation effectively improved within the re-entrant corners. At an oblique wind angle, the swirl flow at the corners increased, and building interference and the sheltering effect decreased. The stagnation point at the leeward side of the building and the wind catchment effect at the re-entrant corners also contributed to the low normalized wind speed. At a wind incident angle of 45°–67.5°, the wind catchment effect decreased due to an increase in swirl flow at the corners. Fresh air rarely entered the re-entrant corners on the leeward sides of the buildings at a perpendicular wind direction. By changing the aspect ratio, wind circulation can be improved on the leeward sides of buildings, as shown in Case 3 ($\lambda = 2.84$) for all configurations. In addition, the vortex region shifted outward and diminished with variations in the wind incident angle. An unstable vortex was observed at an oblique wind direction in the re-entrant corners. Previous studies have indicated that an unstable vortex increased wind circulation, which provides suitable conditions for the dispersion of contaminants. At a low aspect ratio, the wind circulation improved within the re-entrant corner, which indicates that the flow rate within the re-entrant corners can be improved with an extensive building separation or suitable building orientations.

Wind comfort analysis of the various configurations revealed that a small difference in passage flow was detected at the aspect ratios 2.84 and 3.76 compared with the aspect ratio 7.45, which indicates that wind thrust in the passages decreased with increasing building separations. As previously mentioned, each sensor represented a specific area. Among square-, U-, L-, and I-shaped building arrangements, the square-shaped building arrangement yielded a higher average acceptable wind speed area at lower aspect ratios. However, higher wind speed area was infrequently observed. High wind speeds around building is required for contaminant dispersion. Regarding both acceptable and high wind speed areas, U- and L-shaped arrangements produced superior results (Tables 14 and 15). In U- and L-shaped arrangements, the L-shaped arrangement produced superior results regarding high wind speed areas at low aspect ratios, which was

| Case 1 (°) | No of sensors | Case 2 (°) | No of sensors | Case 3 (°) | No of sensors |
|-----------|---------------|-----------|---------------|-----------|---------------|
|           | L | A | H | L | A | H | L | A | H |
|           | E | S | E | S | E | S | E | S | E | S | E | S | E | S | E | S |
| 0°        | 4  | 4  | 29 | 29 | 15 | 15 | 0° | 3  | 7  | 43 | 39 | 14 | 14 |
| 22.5°     | 5  | 5  | 27 | 29 | 16 | 14 | 22.5° | 3  | 4  | 41 | 41 | 16 | 15 |
| 45°       | 2  | 2  | 30 | 31 | 16 | 15 | 45° | 2  | 3  | 37 | 38 | 21 | 19 |
| 67.5°     | 3  | 4  | 29 | 30 | 16 | 14 | 67.5° | 2  | 3  | 39 | 40 | 19 | 17 |
| 90°       | 6  | 6  | 24 | 26 | 18 | 16 | 90° | 5  | 4  | 37 | 39 | 18 | 17 |
|           |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
attributed to unrestricted air movement caused by open sides and low building drag. In an L-shaped arrangement, no major difference was obtained in average acceptable wind speed areas at a low aspect ratio (3.76). However, a small difference was observed at the aspect ratio 2.84 in I- and L-shaped arrangements.

The flow behavior in all configurations was completely inhomogeneous, and the flow pattern varied for each wind direction. Of the three cases, the acceptable wind area for a lower aspect ratio was larger than the acceptable wind area for a higher aspect ratio. This was found to be suitable for pedestrian wind comfort. A high wind thrust inside deep, narrow passages or in building corners is common, especially during winter in subtropical regions. The findings indicated that the wind velocity distributions at lower aspect ratio were stable, which is suitable for winter. However, a high wind speed is required in summer to diminish thermal stress. The results revealed that the difference between both sides (near- and far-field) of the normalized wind speed was high at a high aspect ratio. However, for a lower aspect ratio, the difference decreased due to the reduced venturi effect. Wind-dominant conditions were observed around the buildings and within the re-

### Table 13

| θ  | % Area of the wind speed regions (λ = 7.45) | % Area of the wind speed regions (λ = 3.76) | % Area of the wind speed regions (λ = 2.84) |
|----|------------------------------------------|------------------------------------------|------------------------------------------|
|    | E  | S  | H  | E  | S  | H  | E  | S  | H  | E  | S  | H  | E  | S  | H  | E  | S  | H  | E  | S  | H  | E  | S  | H  | E  | S  | H  |
| 0° | 19 | 21 | 60 | 21 | 19 | 15 | 13 | 70 | 15 | 15 | 10 | 10 | 77 | 13 | 12 | 15 | 70 | 72 | 70 | 73 | 73 | 73 |
| 22.5° | 15 | 17 | 63 | 60 | 23 | 23 | 5  | 5  | 75 | 20 | 20 | 8  | 5  | 67 | 25 | 23 | 8  | 67 | 72 | 75 | 73 | 73 | 73 |
| 45° | 2  | 6  | 77 | 77 | 21 | 17 | 2  | 3  | 73 | 25 | 25 | 0  | 0  | 67 | 33 | 32 | 0  | 67 | 68 | 67 | 67 | 67 | 67 |
| 67.5° | 4  | 6  | 65 | 67 | 31 | 27 | 2  | 0  | 70 | 28 | 28 | 2  | 3  | 75 | 23 | 23 | 2  | 75 | 73 | 73 | 73 | 73 | 73 |
| 90° | 13 | 13 | 52 | 56 | 35 | 31 | 8  | 5  | 67 | 25 | 25 | 8  | 2  | 63 | 28 | 30 | 8  | 63 | 68 | 68 | 68 | 68 | 68 |
| Ave. | 10.6 | 12.6 | 63.4 | 64 | 26.2 | 23.4 | 6.4 | 5.2 | 71 | 22.6 | 22 | 5.6 | 4.0 | 69.8 | 24.4 | 24 | 5.6 | 69.8 | 71.8 | 24.4 | 24 | 71.8 | 71.8 |

Fig. 16. Contour of NWS of different cases of Configuration 4 at the pedestrian level in the (a) numerical simulation and (b) wind tunnel experiment.
entrant corners, which can be achieved via proper building separa-
tion and oblique prevailing wind directions.

This study was limited to a wind flow analysis using a steady
RANS approach. Numerical errors can be reduced by selected more
advanced numerical techniques, such as LES and a hybrid unsteady
RANS/LES approach. Future studies will focus on the turbulence
parameters, pollution dispersion at the re-entrant corners, and the
influence of vegetation on the wind environment from various
wind incident directions.

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