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Effects of lift-up design on pedestrian level wind comfort in different building configurations under three wind directions

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Abstract

The pedestrian level wind environment is seriously deteriorated by moderated local wind flow in a densely built-up subtropical city like Hong Kong. In order to improve the weak wind condition, the lift-up design has been used for some time. However, there is a lack of understanding and quantitative assessment of its modification on the pedestrian level wind comfort around different building configurations under different wind directions. This paper aims to study the effects of lift-up design in four common building configurations on the wind comfort via computational fluid dynamics (CFD) simulations. The turbulence model and numerical method are firstly validated by comparing the simulated wind flow data with the wind tunnel test results. The validated model is then utilized to simulate the four building configurations, including the "一", "L", "U" and "□" shaped buildings. The mean wind velocity ratio (MVR) and mean wind velocity change ratio (ΔMVR) are employed to identify the wind comfort and to quantitatively evaluate the improvements due to the lift-up design. Results show that the lift-up design can improve the wind comfort in building surroundings and its influence is highly dependent on the incident wind direction. Specifically, the wind comfort is better under the oblique wind direction than the other two wind directions. These findings can provide us a better understanding of the lift-up design and will be helpful in better precinct planning.

Keywords: *Lift-up design; Pedestrian level wind comfort; CFD simulation; Mean wind velocity ratio (MVR); Mean wind velocity change ratio (ΔMVR)*

1. Introduction

The increasing high-rise buildings in densely built-up cities cause moderated air flow at pedestrian level. These result in unfavourable wind velocity and thermal comfort conditions that may eventually affect human health. The issue is more serious in the subtropical urban area, such as the summer in Hong Kong [1-3]. For the purpose of improving the wind flow in a densely built-up city scale, Li et al. [4] proposed the concept of city ventilation that is composed of the evaluation parameters including air change rate [5], age of air [5] and ventilation efficiency [6]. Besides, the air ventilation assessment (AVA) scheme proposed by the Hong Kong SAR government aims to enhance the wind movement at pedestrian level in Hong Kong [1]. It is obvious that in the hot and humid Hong Kong, pedestrian level wind flow is of great importance to pedestrian thermal comfort.

Wind comfort has become a pressing issue over the last decades, since the achievement of an acceptable wind comfort around the buildings is difficult in most urban areas. Previous studies mainly focused on the discomfort conditions caused by the strong wind around the buildings [7-10]. However, increasing awareness and concerns are about the unfavourable pedestrian level wind environment caused by low wind velocities around buildings in the densely built-up urban areas [1-5, 11-13]. Unlike the evaluation of outdoor thermal comfort that consists of bio-metrology index such as thermal perception and human adaption parameters [14-16], the pedestrian level wind comfort mainly focuses on the effect of the wind force on humans. In order to evaluate the wind comfort in a practical situation, numerous wind comfort criteria have been proposed in the past decades [17-20]. Evaluation of the wind comfort can be achieved by combing the wind flow characteristics with wind comfort criteria and local wind statistics. The wind flow characteristics are obtained either from wind tunnel or from numerical simulation. Tsang et al. [12] studied the pedestrian level wind environment around tall buildings with different building dimensions, separations and podium designs using wind tunnel tests. Their results show that the wide building with the podium design tends to obtain weak wind condition at pedestrian level. Besides, CFD simulation has been intensively used for studying the indoor and outdoor environment of buildings [7, 21-30] and also has been broadly employed in investigating the wind flow around the building envelopes, especially at pedestrian level [31-33]. Mochida and Lun [31] reviewed the predictions of pedestrian level wind and thermal comfort that has been achieved by environment engineering researchers in Japan. Besides, the studies of wind environment around buildings at pedestrian level was detailed reviewed by Blocken et al. [33] and referred to the accuracy of the wind comfort assessment using wind tunnel and CFD simulation techniques.

In order to improve the weak wind condition at pedestrian level in densely built-up urban areas, many new types of wind passages are introduced into building design and urban planning [13, 34-36]. The lift-up design, in which the building block is "lifted" off the ground supported by the modern structural pillar, can be regarded as one of the prominent design because it is feasible to implement. This design has gained increasing attention in south-eastern Asian cities, like Hong Kong. A majority of Hong Kong's public amenity venues and transportation interchanges are located in the lift-up areas underneath the high-rise buildings. However, the potential benefits of the lift-up design in improving the weak wind condition at pedestrian level have not been totally explored or understood. Previous studies have already shown that the lift-up area can create a local cooling spot for the pedestrian activities in hot and humid Hong Kong, which can in turn encourage more outdoor activities [13, 35, 36]. Xia et al. [35] studied the pedestrian level wind environment with lift-up design underneath three tall buildings by wind tunnel modelling. Their results show that the lift-up design can enhance the air flow around buildings. Liu et al. [36] investigated the thermal comfort around the lift-up building surroundings via CFD simulation and indicated that the lift-up design can improve the thermal comfort at pedestrian level but limited to the neighbouring area. The above researches have proven the advantages of lift-up design on pedestrian level wind environment. However, the pedestrian level wind comfort around the buildings with lift-up design and the effects of lift-up design on the wind environment have not been clearly identified.

This research aims to provide an insightful understanding about the effects of lift-up design on pedestrian level wind comfort in different building configurations. Four typical existing building configurations with the lift-up design at the Hong Kong Polytechnic University (HKPolyU) campus are chosen in this study. Since the wind flow pattern is highly dependent on the incident wind direction, three typical wind directions are selected, including normal, oblique and parallel approaching wind directions. This paper is organised as follows: after the introduction, the wind flows around the building configurations with and without lift-up design are given in Section 2, which are simulated via CFD technique using the Steady Reynolds Averaged Navier-Stokes (SRANS) re-normalization group (RNG) k-ε turbulence model. The MVR is defined in Section 2.2, which is used to evaluate the pedestrian level wind comfort in the later section. Besides, the ΔMVR is proposed in Section 2.3 to quantitatively assess the effects of the lift-up design. In addition, the validation between the numerical results with the experimental data obtained from the wind tunnel test is given in Section 2.4. Section 3 demonstrates the geometry description of four building configurations, including "—", "L", "U" and "□" shaped buildings. In Section 4, the validated CFD models are employed to simulate the wind flow around buildings with and without lift-up design under three wind directions. The simulated results are used to evaluate the pedestrian level wind comfort with lift-up building and quantitatively assess the effects of lift-up design on pedestrian level wind environment. Finally, Section 5 concludes the paper.

2. Methodology

2.1 CFD turbulence models

The modified, RNG k-ε turbulence model is applied in this study for the following considerations: i) this paper only focuses on the mean wind velocity at pedestrian level; ii) it is indicated in reference [33] that the SRANS modelling approaches can provide sufficient accuracy at economic numerical cost; iii) SRANS turbulence models have been most commonly used and reliable CFD approach in wind engineering [7, 23, 24, 26, 36-38].

The general form of the time-averaged governing equation for the neutral and incompressible fluid can be written as the following equation [39]:

$$\frac{\partial}{\partial_t}(\varphi) + \nabla(\overline{u}\varphi) = \nabla\left(\Gamma_\varphi \nabla_\varphi\right) + S_\varphi \quad (1)$$

where, φ stands for the scalars: the velocity components, $\mathrm{u(m/s)}$, $\upsilon\mathrm{(m/s)}$ and $\mathrm{w(m/s)}$; the turbulent kinetic energy $\mathrm{k}(m^2/s^2)$ and the turbulent dispassion rate $\varepsilon(m^2/s^3)$. $\overline{u}$ represents the mean velocity vector; Γ_φ is the effective diffusion coefficient for each dependent variables; S_φ is the source term in this equation.

For the turbulent kinetic energy:

$$\Gamma_\varphi = \alpha_k \mu_{eff} \quad (2)$$

For the turbulent dispassion rate:

$$\Gamma_\varphi = \alpha_\varepsilon \mu_{eff} \quad (3)$$

where, μ_{eff} represents the effective turbulent viscosity; α_k and α_ε are the inverse effective Prandtl numbers for k and ε, respectively.

The turbulent viscosity in the RNG k-ε turbulence model is given as the following forms[45]:

$$\mathrm{d}\left(\frac{\rho^2 k}{\sqrt{\varepsilon\mu}}\right) = 1.72 \frac{\hat{\upsilon}}{\sqrt{\hat{\upsilon}^3 - 1 + C_\upsilon}} d\hat{\upsilon} \quad (4)$$

where, $\hat{\upsilon} = \frac{\mu_{eff}}{\mu}$ and $C_\upsilon \approx 100$

The differential equation of the turbulent viscosity provides accurate relationship between the turbulent transport and the Reynolds number. In the high-Reynolds-number conditions the equation (4) can be written as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

where, ρ (kg/m^3) is the fluid density and C_μ is a constant equals to 0.085.

The RNG k-ε turbulence model shows a number of refinements over the standard k-ε turbulence model, partly owing to the additional strain-dependent term, R_ε, which makes the RNG k-ε turbulence model more adept at solving the rapid strain and streamline curvature.

$$R_\varepsilon = \frac{C_\mu \rho \eta^3 (1-\eta/\eta_0)}{1+\beta\eta^3} \cdot \frac{\varepsilon^2}{k} \quad (6)$$

where, C_μ, η_0 and β are constants here: $\eta_0 = 4.38$, $\beta = 0.012$. And $\eta = Sk/\varepsilon$, which S is the scale of strain rate.

2.2. Pedestrian level wind parameters

The present study uses the mean wind velocity to evaluate pedestrian level wind comfort, considering that the mean wind velocity with an average time of an hour is regarded to be more representative for low wind velocity conditions than gust wind velocity with an averaging period lasting 2-3 seconds [12]. In order to make the findings universal, normalized mean wind velocity known as the mean wind velocity ratio (MVR) is employed in the study, because it can readily combine with a specific wind climate (magnitude and probability of exceedance) to determine the wind comfort. The MVR is defined as follows:

$$\text{MVR} = U_p/U_r \quad (7)$$

here, U_p, stands for the mean wind velocity at any spot at the pedestrian level, while U_r is the reference mean wind velocity of the approaching flow at 200m in prototype scale, which is considered to be not affected by the urban architecture complex.

In order to quantitatively assess the effects of lift-up design on the pedestrian level wind environment, the mean wind velocity change ratio (ΔMVR) is proposed. This is achieved by firstly investigating the wind flow around the two distinctive building configurations: the building with lift-up design and the identical building without lift-up design, and obtain the values of MVR around the buildings at pedestrian level. The ΔMVR between the two buildings is then calculated as the following equation:

$$\Delta\text{MVR} = (MVR_{LU} - MVR_{NLU})/MVR_{NLU} \quad (8)$$

where, the subscript LU means building with lift-up design, and the subscript NLU means building without lift-up design. MVR_{LU} is the value of MVR at any spot at pedestrian level with the lift-up design, while MVR_{NLU} is the value of MVR at the same spot at pedestrian level without lift-up design.

2.3. Identification of pedestrian level wind comfort

According to the Hong Kong Planning Department [41], the annual average mean wind velocity at 200m reference height is 5m/s at the location of the HKPolyU campus and the probability of exceedance is approximately 50%. In order to reach the threshold value of 1.5m/s, which is the minimum noticeable wind velocity for human [42] and also meets the requirement for a person to achieve neutral thermal sensation in hot and humid Hong Kong [3] , an MVR value equal or over 0.3 is required in this study to maintain a favourable wind environment for pedestrian activities. Besides, this threshold value also corresponds to the air ventilation assessment (AVA) scheme in Hong Kong, which aims to enhance wind flow movement at pedestrian level [1]. It should be mentioned that the value of MVR less than 1 satisfies the requirement for sitting long in the NEN 8100 (2006) wind comfort criteria [20] (For sitting long, the threshold mean wind velocity is 5m/s and the exceedance probability is less than 2.5%). Therefore, areas with MVR values less than 0.3 are designated as low wind velocity zones that are uncomfortable for pedestrian activities. In addition, it can be considered that the higher value of MVR (less than 1), the more wind comfortable for pedestrian activities in hot and humid Hong Kong.

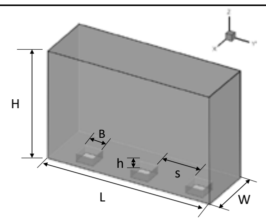
2.4. Turbulence model validation

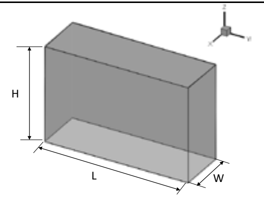
2.4.1 Case description

The wind tunnel test conducted by Xia et al. [35] is employed as the validation case, which was tested at a scale of 1:200 in the CLP power Wind/Wave Tunnel Facility (WWTF) at Hong Kong University of Science and Technology (HKUST). The descriptions of the two building configurations:

with and without lift-up design are shown in Table 1. The similarity requirements between the model and the prototype were strictly examined during the test. In order to reproduce the original full-scale flow, a series of similarity criteria should be satisfied. The geometric and boundary layer flow similarities are easily achieved when the scaled model, computational domain and boundary conditions are appropriately selected. The threshold Reynolds number of 15,000 recommended by Meroney [45] should be carefully reached. The approaching wind velocity in this study is around 5m/s at the building roof, resulting in a R_e number of at least 5.4×10^4 ($R_e = V_z D_z / \upsilon$), which can be regard as large enough to obtain R_e number independence in this study. Besides, building configurations with and without lift-up design were investigated in the test. Fig.1 shows the vertical approaching wind velocity profile and the turbulence intensity of the test. Also, it demonstrates that measurement accuracies during the test were within 5%. The vertical approaching wind velocity followed the form of power law with the exponent of 0.2 ($U(z)/U_r = (Z/Z_r)^{0.2}$). The mean wind velocity U_r at the reference height (150m in prototype scale, 0.75m in model scale) was 10m/s. The approaching wind profile and the turbulence intensity defined in the CFD simulation are directly interpolated from the experiment. The mean wind velocities which were measured during the experiment are employed in this study to validate the computational model.

Table 1. Dimensions of the building model with and without lift-up design

Building type	Building model	Building height (H) (m)	Building length (L) (m)	Building width (W) (m)	Lift-up design height (h) (m)	Lift-up design spacing (s) (m)	Lift-up design dimension (B) (m)	Total height (TH) (m)
With lift-up design		50	75	25	3.5	17.5	8×8	53.5

Without lift-up design		50	75	25	N/A	N/A	N/A	50

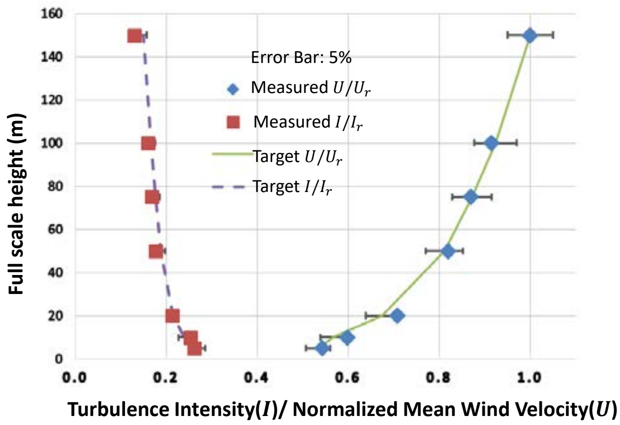


Fig. 1. Approaching vertical wind profile of turbulence intensity and normalized wind velocity.

2.4.2 Boundary conditions and numerical methods

The upstream, downstream, lateral, and height length of the computational domain are 5H, 15H, 5H and 5H, respectively. This computational setup meets the requirements of the CFD practice guidelines [43, 44], which is large enough to ensure that the wind flow is fully developed in the domain outlet. The boundary conditions used in this study are listed in Table 2. The whole computational domain is constructed with the hexahedra grids. Fig. 2 shows the horizontal lines at pedestrian level plan ($Z/H = 0.01$) at which the experiment data and the simulation results are compared. The pressure and momentum equations are coupled using the SIMPLEC algorithm, and the second-order upwind scheme is utilized in the discretization scheme. The residuals in the simulation are all set as 10^{-6}. Three different mesh systems with the minimum grids size of 0.005m, 0.001m and 0.0005m are built and the simulation results of the three mesh systems are compared in order to examine the independence of the numerical solution on the grid size. The three mesh systems can be seen in Fig.3. The mesh numbers for the three mesh system are 1.82 million, 3.72 million and 5.51 million, respectively. Fig.4 presents the comparison of the values of MVR produced by three types of grid size scales at the line of $X/H = -0.25$ with lift-up design. It is clear that the minimum grid size of 0.001m can provide sufficient accuracy at the economic computing cost. Besides, the y^+ values of the first near-wall grids in the vicinity of the building surface and ground are less than 5 when the minimum grid size is 0.001m. Therefore, the minimum grid size of 0.001m is adopted in this study.

Table 2. Boundary conditions of the computational domain

Domain inlet	Interpolation from the wind tunnel wind profile
Domain outlet	$\partial/\partial x(u, v, k, \varepsilon) = 0$
Domain ceiling	$\mathrm{w} = 0, \partial/\partial x(u, v, k, \varepsilon) = 0$
Domain lateral	$v = 0, \partial/\partial x(u, v, k, \varepsilon) = 0$
Domain ground	Enhanced wall functions
Building surface	Non-slip for wall shear stress

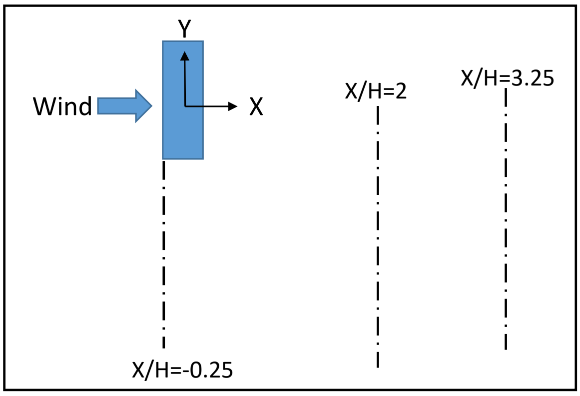


Fig. 2. Comparison lines at pedestrian level plan.

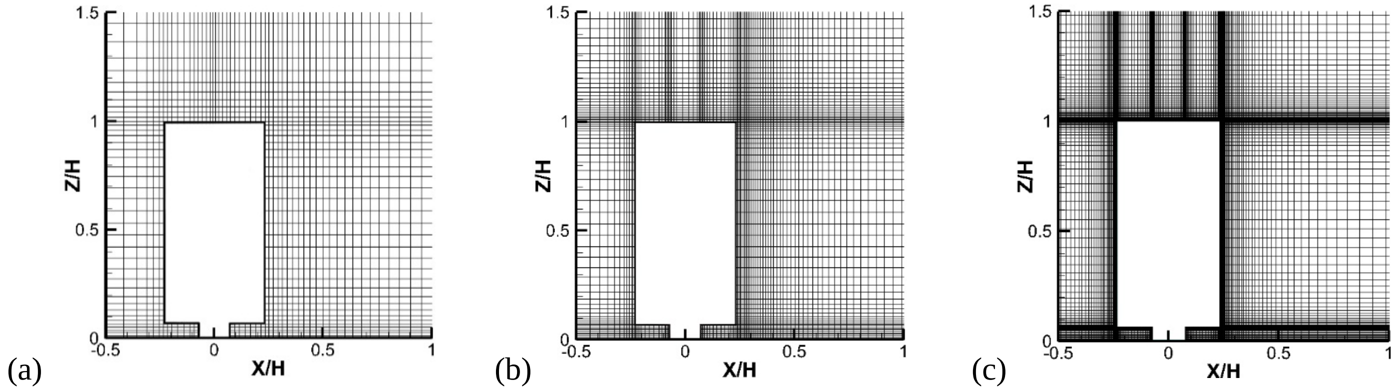


Fig. 3. Mesh details of the vertical centre plane of the computational domain ($y = 0$): (a) minimum grid size of 0.005m; (b) minimum grid size of 0.001m; (c) minimum grid size of 0.0005m.

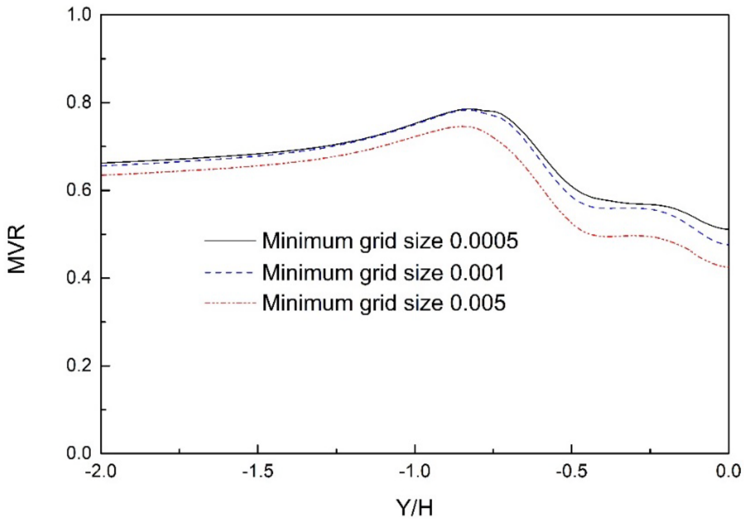


Fig. 4. Comparison of values of the MVR produced by three types of mesh system at the line of $X/H = -0.25$ with lift-up design.

The comparison between the wind tunnel data and the simulated results with and without lift-up design are presented in Fig.5 and Fig.6, respectively. As for the windward side of the building, the simulation results of the buildings with and without lift-up design agree very well with the experiment data except for some subtle differences, see fig.5 (a) and fig.6 (a). As for the windward side of the building, the simulation results of the buildings with and without lift-up design agree very well with the experiment data except for some subtle discrepancies, see fig.5 (a) and fig.6 (a). For the leeward side of the buildings, fig. 5(b) and fig.6 (b) demonstrates that the CFD simulations present very good performance for the building with lift-up design while a little overestimate for the building without lift-up design when $X/H = 2$. Besides, fig. 5(c) and fig.6 (c) shows that the simulation results have good agreement with experiment data, even for some minor discrepancies when $X/H = 3.25$. Therefore, it can be concluded that the selected turbulence model and numerical method can provide sufficient accuracy for predicting the wind flow around the buildings with and without lift-up design.

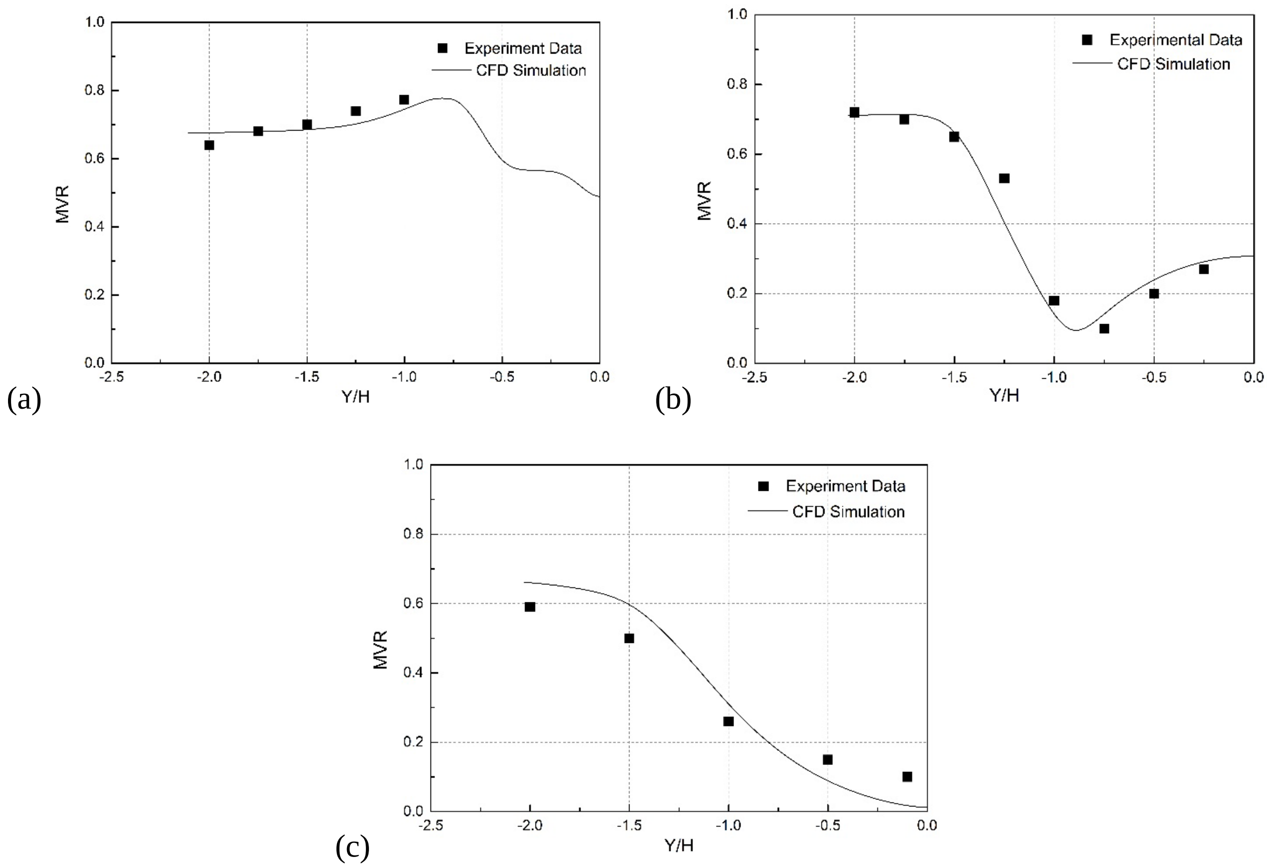


Fig. 5. Comparison of values of the MVR between wind tunnel data and numerical results with lift-up design: (a)$X/H = -0.25$; (b)$X/H = 2$; (c)$X/H = 3.25$.

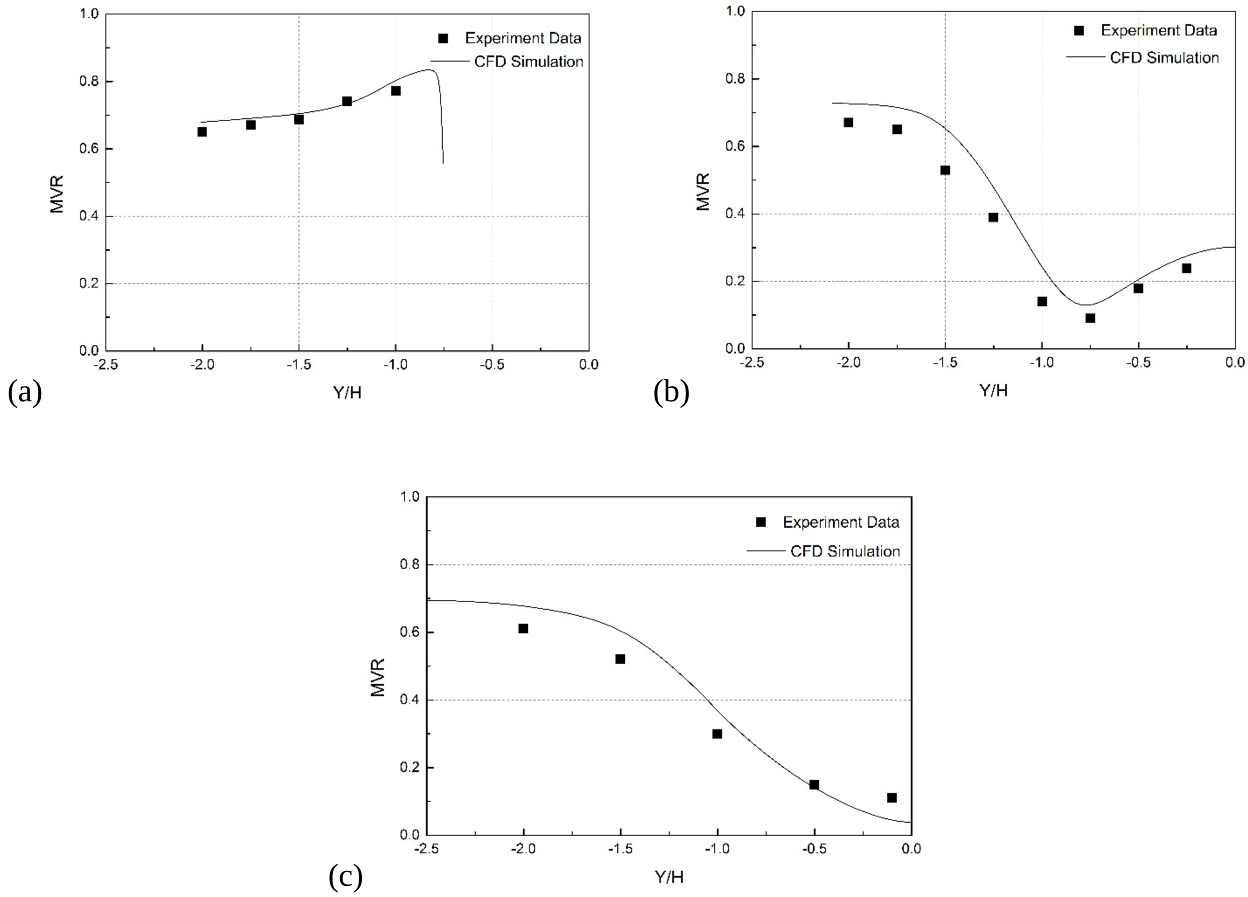


Fig. 6. Comparison of values of the MVR between wind tunnel data and numerical results without lift-up design: (a)$X/H = -0.25$; (b)$X/H = 2$; (c)$X/H = 3.25$.

3. Building Configuration Description

In order to study the effects of lift-up design on pedestrian level wind comfort, the lift-up design in HKPolyU campus is selected. Four common building configurations at the campus are studied in 1:200 scale. The “一” shaped building (Fig. 7 (c)) is presented here as the basic building configuration and its dimension is schematically shown in prototype in Fig. 7 (a)-(b). Fig. 7 (d)-(f) presents the other three building configurations: the “L” shaped building, the “U” shaped building and the “□” shaped building, which are based on the “一” shaped building. Apart from the normal approaching wind directions (θ=0°), the current study also considers the oblique approaching wind directions (θ=45°) and the parallel approaching wind directions (θ=90°), seen in Fig. 7(g). It should be noted that the meshes of all simulated cases in Section 4 are generated by hexahedra grids. Similarly, the same inflow wind profile and the computational domain size are referred as the validation cases in Section 2.4. In the meantime, the validated turbulence model and numerical methods in Section 2.4 are used in the wind flow simulations around the four building configurations.

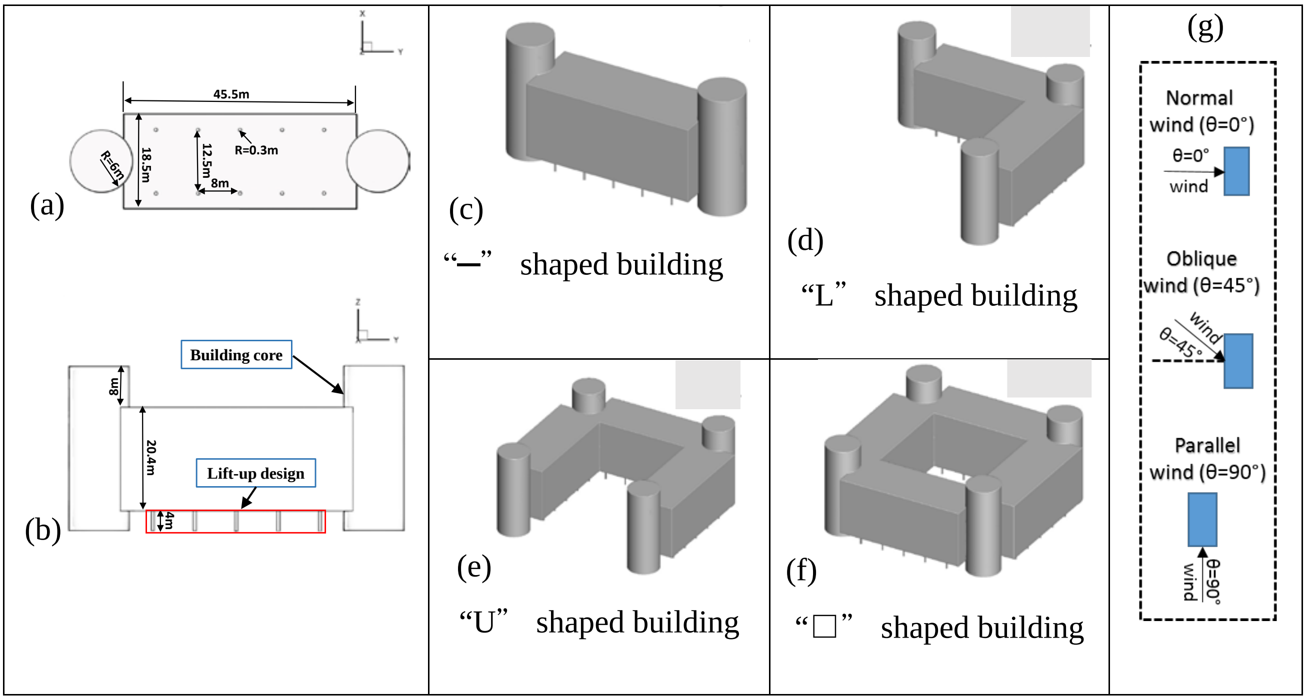


Fig. 7. The basic building dimension (a)-(b), case studied (c)-(f) and wind directions (g).

4. Results and Discussion

4.1. The effects of lift-up design in the “—” shaped building

The general features of the MVR distributions around the “—” shaped buildings with and without lift-up design under the normal wind direction are shown in Fig. 8. It can be seen that three wind velocity zones: upstream low wind velocity (ULWV) zone, lateral high wind velocity (LHWV) zone, and downstream far-filed low wind velocity (DFLWV) zone are indicated both around the building with and without lift-up design. However, there are two different wind velocity zones in these two building configurations, which are shaded in Fig. 8. One is the downstream near-filed low wind velocity (DNLWV) zone which is replaced by the near-field high wind velocity (DNHWV) zone when the building is elevated with the lift-up design. The reason is that the wind flow passes through the lift-up area directly, which is illustrated in Fig. 9. Another one is a local wind amplification zone underneath the elevated building, resulting in the lift-up wind velocity (LUWV) zone. This phenomenon can be explained by the Venturi Effect.

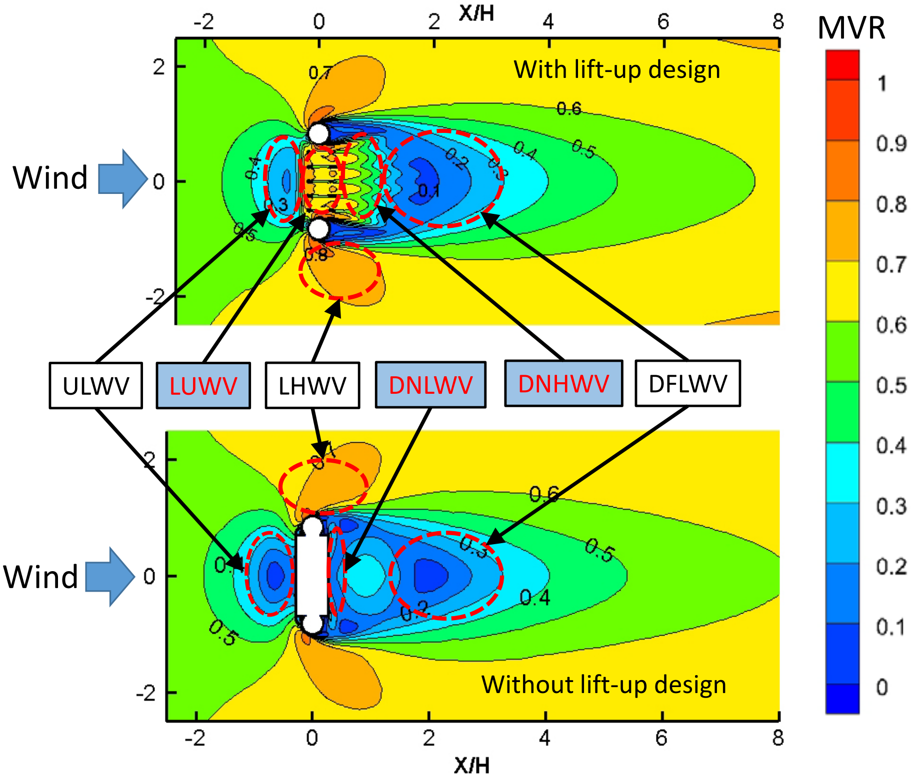


Fig.8. General features of the MVR distributions at pedestrian level around the "一" shaped building under the normal wind direction: (a) with lift-up design; (b) without lift-up design.

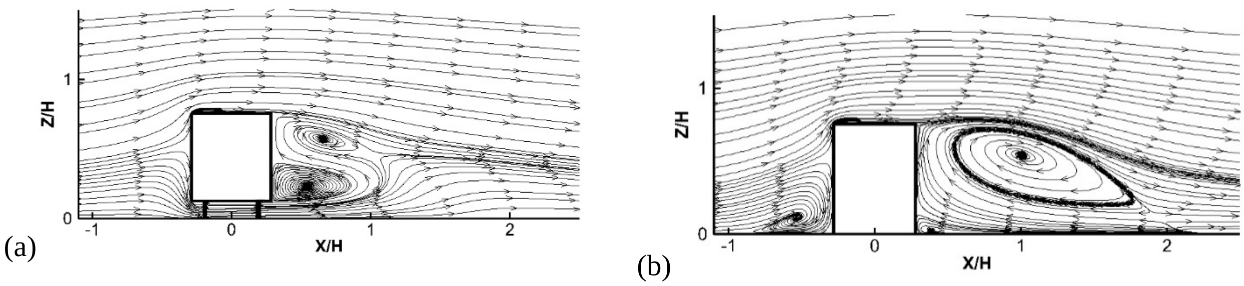


Fig. 9. Wind flow pattern with streamlines on the x-z plane at $y/H = 0$ under the normal wind directions: (a) with lift-up design; (b) without lift-up design.

Fig. 10 shows the MVR distributions around the “一” shaped building with lift-up design at pedestrian level under the oblique and parallel wind direction; the MVR distributions under the normal wind direction is presented in Fig. 8 (a). Under the oblique wind direction, the MVR flow pattern shifts slightly to the downstream of building and the most affected area changed from the centreline of the building to the downstream side (Fig. 10(a)).

It can be observed that for the high wind velocity zones, the LHWV zone is wind comfortable ($MVR \geq 0.3$) for the pedestrian activities under three wind directions while the LUWV zone and DNHWV zone are only wind comfortable under the normal and oblique wind directions. The low wind environments of LUWV zone and DNHWV zone under the parallel wind direction result from the blockage effect of the building cores. For the low wind velocity zones, the ULWV zone and DFLWV zone are wind uncomfortable ($MVR < 0.3$) under three wind directions. It is clear that the area of ULWV zone and DFLWV zone are much smaller under the oblique wind direction than that under the normal wind direction. Even though the total areas of the wind uncomfortable zone under the oblique and the parallel wind direction are almost the same, the advantages of lift-up design are not fully exploited under the parallel wind direction. Therefore, as for the “一” shaped building with lift-up design, the pedestrian level wind comfort is generally better under the oblique wind direction than the other two wind directions.

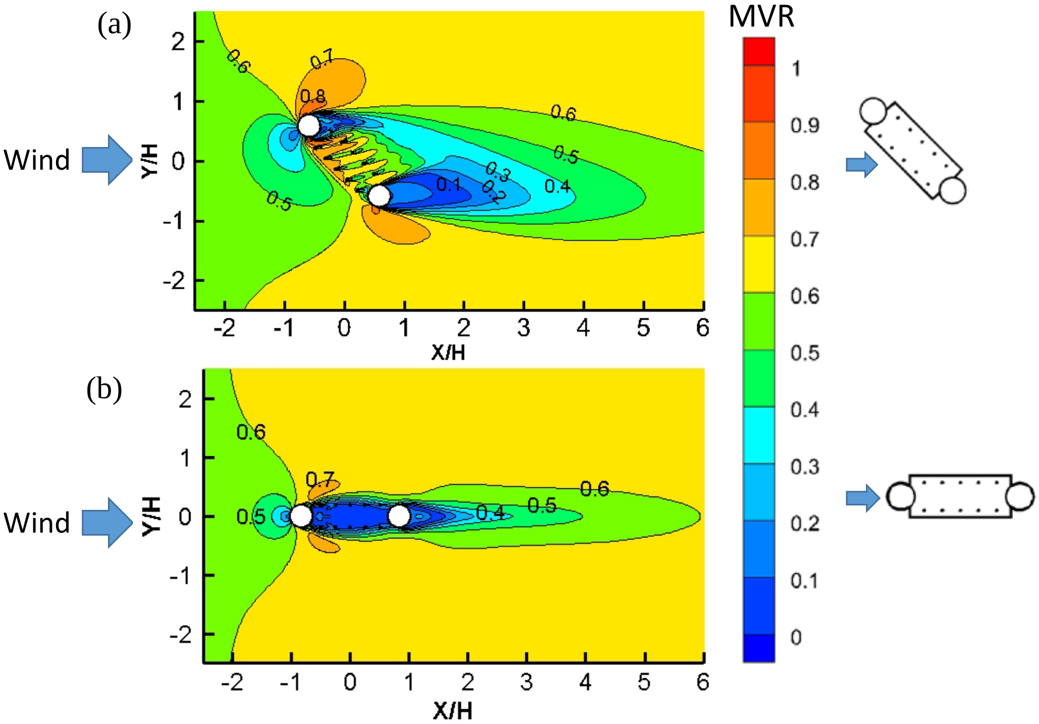


Fig. 10. MVR distributions around the "—" shaped building with lift-up design at pedestrian level under different wind directions: (a) Oblique wind (θ=45°); (b) Parallel Wind (θ=90°).

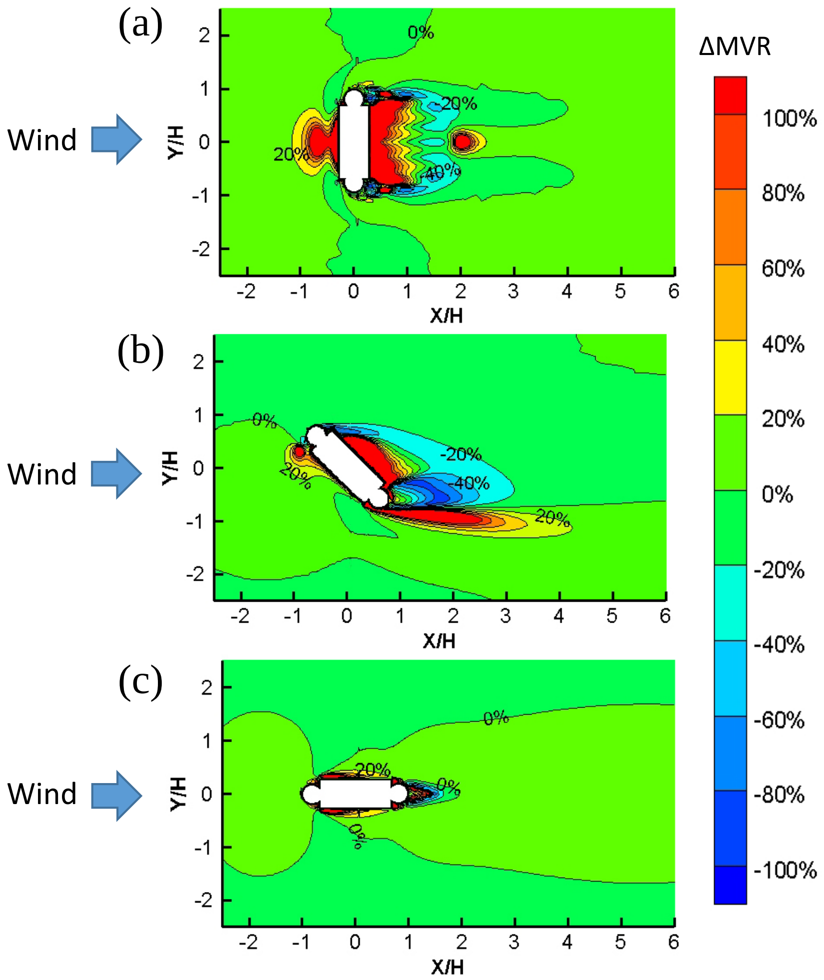


Fig. 11. Effects of lift-up design around the "—" shaped building at pedestrian level under three wind directions: (a) Normal wind (θ=0°); (b) Oblique wind (θ=45°); (c) Parallel Wind (θ=90°).

To quantitatively assess the effects of the lift-up design on pedestrian level wind environment, the ΔMVR distributions around the "—" shaped building under three wind directions are presented in Fig. 11. It is clear that the significant wind amplification effect caused by the lift-up design occurs around the building, and the amplification effect decreases as the distance from leeward face of the building become farther. Besides, it is interesting to find that the values of ΔMVR become negative in some places of the leeward side, which means that the values of MVR decrease in this spot when the lift-up design is used. This is because a part of wind flow is induced to the upper stratum due to the vortexes behind the building, see Fig. 9. Thus, the strength of the horizontal flow with lift-up design is weaker than the strength of the reattachment flow of the vertical recirculation without lift-up design at the same spot. Furthermore, the values of MVR in the ULWV zone and DNLWV zone under the normal and oblique wind direction are greatly enhanced due to the lift-up design. However, the results of MVR around the "—" shaped building are insensitive to the lift-up design under the parallel wind direction.

4.2 The effects of lift-up design in the "L" shaped building

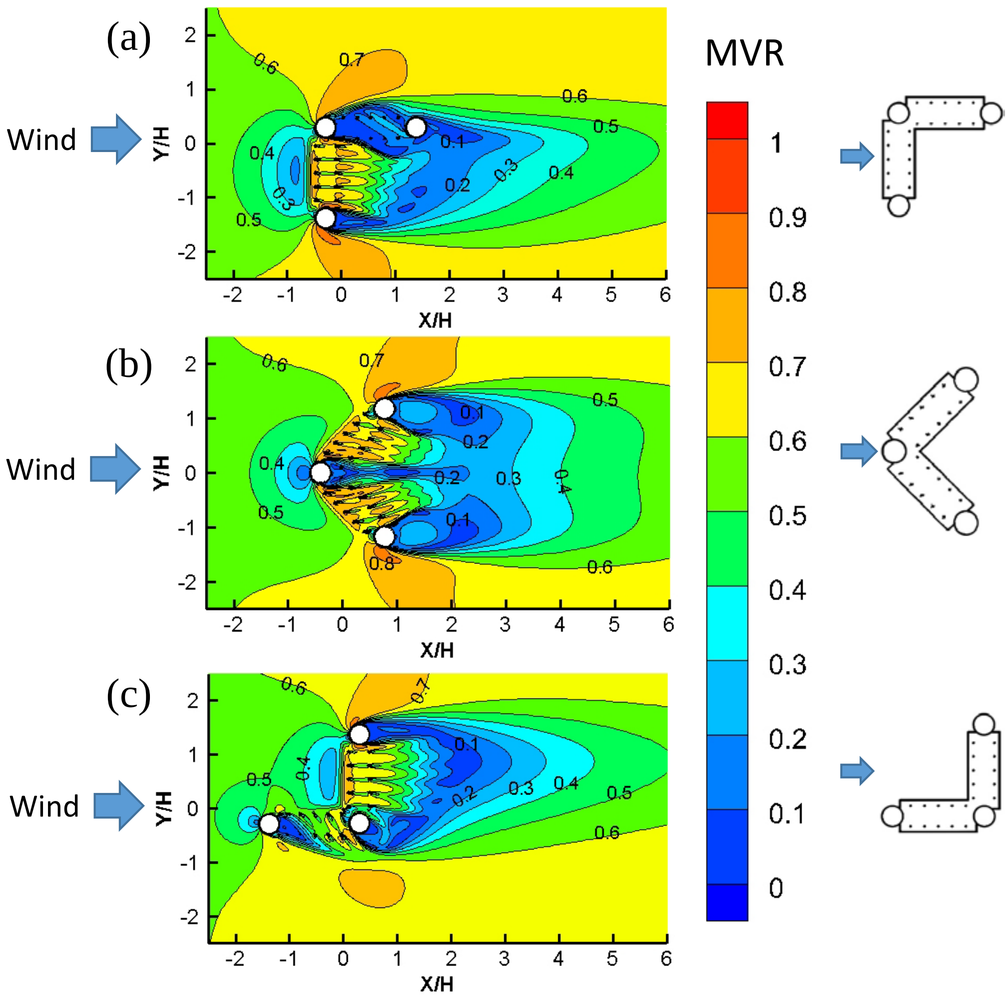


Fig. 12. MVR distributions around the "L" shaped building with lift-up design at pedestrian level under three wind directions: (a) Normal wind (θ=0°); (b) Oblique wind (θ=45°); (c) Parallel wind (θ=90°).

Fig. 12 shows the MVR distributions around the "L" shaped building with lift-up design at pedestrian level under three wind directions. It can be seen that the pedestrian level wind comfort in the LUWV zones vary greatly under different wind directions. Under the normal wind direction, the values of MVR in the LUWV zone underneath the upstream block of the "L" shaped building are over 0.6, which indicates wind comfortable for pedestrian activities (Fig. 12(a)). However, the wind environment of LUWV zone underneath the downstream block of the "L" shaped building is wind uncomfortable under the normal wind direction. The distinguished difference can be accounted for the fact that the LUWV zone underneath the upstream block is normal to the approaching wind while the LUWV zone underneath the downstream block is parallel to the approaching wind, which are consistent with the findings of the "一" shaped building. The results of MVR in the LUWV zones are over 0.6 under the oblique wind direction, see Fig. 12(b). It can be found from Fig. 12(c) that under the parallel wind direction, the wind environment of the LUWV zone underneath the downstream block is comfortable while the wind environment of the LUWV zone changes from uncomfortable to comfortable underneath the upstream block.

The LHWV zones present high values of MVR under three wind directions, which are wind comfortable for pedestrian activities. It can also be observed from Fig. 12 that the area of the ULWV zone is smallest under the oblique wind direction among the three wind directions. As for the DFLWV zones, the areas are almost the same under three wind directions. Hence, it can be concluded that the wind environment of the "L" shaped building is more comfortable under the oblique wind direction than the other two wind directions.

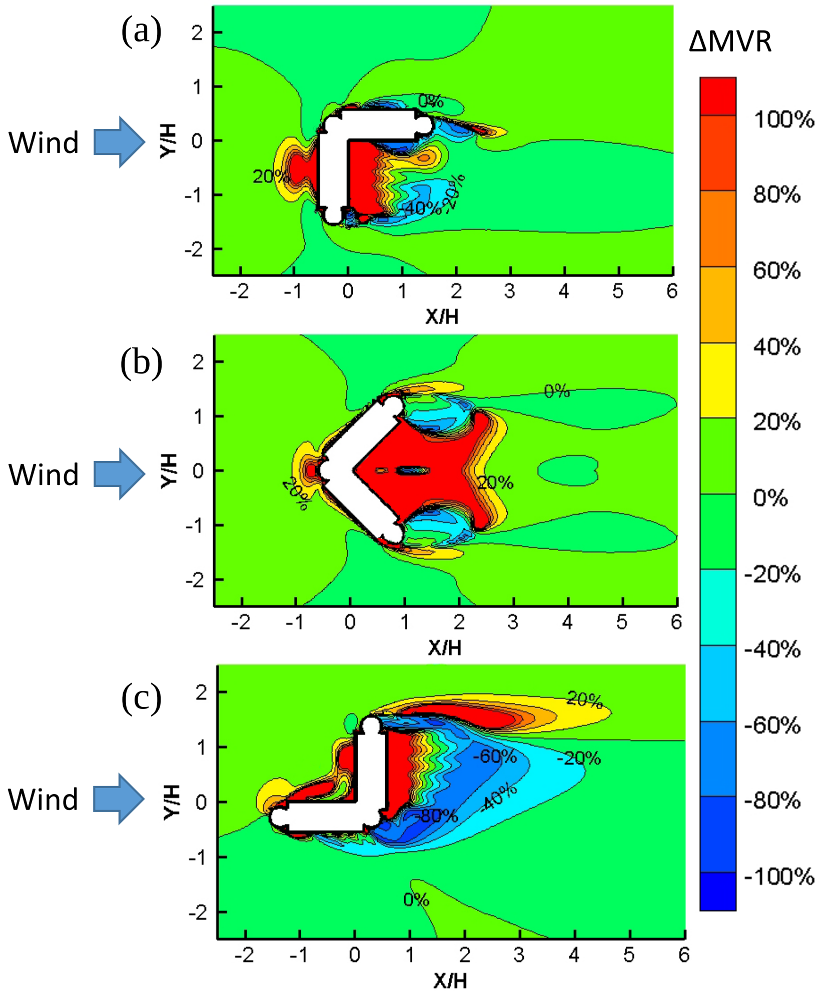


Fig. 13. Effects of lift-up design around the "L" shaped building at pedestrian level under three wind directions: (a) Normal wind (θ=0°); (b) Oblique wind (θ=45°); (c) Parallel wind (θ=90°).

The quantitative display of the effects of lift-up design around the "L" shaped building under three wind directions are presented in Fig. 13. As shown in Fig. 13, the results of MVR in ULWV zone and DNLWV zone are greatly amplified when the lift-up design is adopted in the "L" shaped building. Fig. 13(a) and (c) indicate that the values of MVR around the buildings change slightly when the LUWV zones are parallel to the approaching wind, which are in accordance with the findings of the "—" shaped building. It is noticeable that the values of MVR around the "L" shaped building are remarkably improved by lift-up design under the oblique wind direction, see Fig. 13(b). Furthermore, the results of MVR in the DFLWV zones are reduced evidently under the parallel wind direction (Fig. 13(c)). This can be explained by the following reasons: on the one hand, the flow mechanisms are similar to the case when the approaching wind is normal to the "—" shaped building. On the other hand, the strength of horizontal passing flow at the pedestrian level is weakened by mixing with the bypass flow coming from the lateral side. Above all, it is obvious that the pedestrian level wind environment can benefit more from lift-up design under the oblique wind direction than the other two wind directions for the "L" shaped building.

4.3 The effects of lift-up design in the "U" shaped building

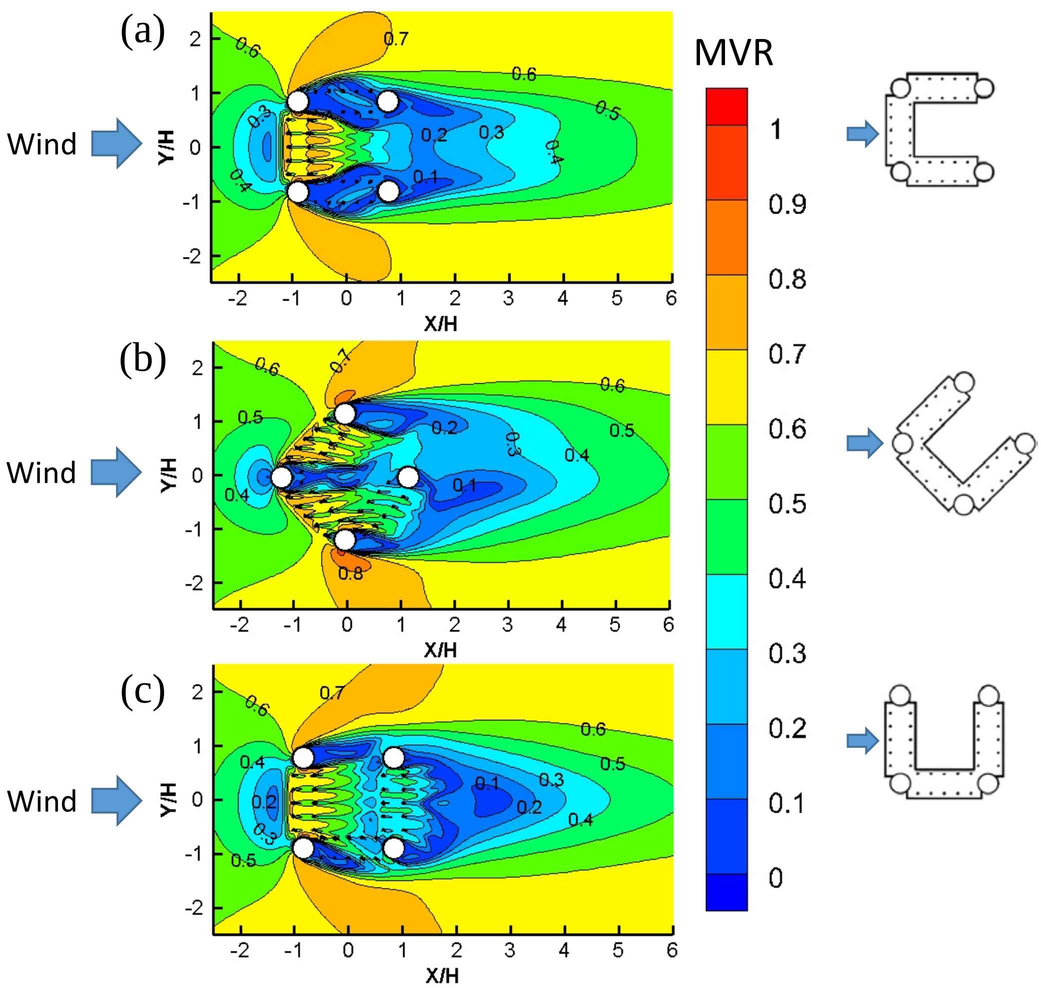


Fig. 14. MVR distributions around the "U" shaped building with lift-up design at pedestrian level under three wind directions: (a) Normal wind (θ=0°); (b) Oblique wind (θ=45°); (c) Parallel wind (θ=90°).

For the horizontal distributions of MVR at pedestrian level with lift-up design underneath the “U” shaped building are shown in Fig. 14. It can be seen from Fig. 14(a) that the wind environment in the LUWV zone underneath the upstream block of the “U” shaped building is very favourable for pedestrian activities under the normal wind direction. However, the LUWV zones underneath the two lateral blocks of the “U” shaped building are wind uncomfortable because the LUWV zones are parallel to the approaching wind. Fig. 14(b) presents that the wind environments of the LUWV zones are comfortable under the oblique wind direction. Even though the wind environments of the LUWV zones are all comfortable under the parallel wind direction (Fig. 14(c)), the values of MVR in the LUWV zone underneath the downstream block are obviously smaller than that underneath the upstream block. This indicates that the strength of the horizontal approaching flow at pedestrian level is seriously weakened by the downwash effect from the windward face of downstream block, which is illustrated in Fig. 15.

The other prominent feature of the “U” shaped building is the semi-closed zone formed by the surrounding blocks. Fig. 14(a) shows that under the normal wind direction, the values of MVR in the semi-closed zones are mostly over 0.4 except for small places on the lateral side. Fig. 14(b) presents that under the oblique wind direction, the semi-closed zone is wind comfortable on the lateral sides while uncomfortable in the middle part because of the blockage effect of the upstream building core. The wind environment is comfortable under the parallel wind direction, but a low wind area in the semi-closed zone exists at the location where the downwash flow from the windward face of downstream block and the horizontal approaching wind flow meet (see Fig. 15).

It is obvious that the LHWV zones are wind comfortable under three wind directions. The area of the ULWV zone is smaller under the oblique wind direction than the other two wind direction. As for the DFLWV zone, which is wind uncomfortable for pedestrian activities, the values of MVR are higher under the oblique wind direction than the other two directions. Overall, the wind comfort at pedestrian level is better under the oblique wind direction than the other two wind directions for the "U" shaped building with lift-up design.

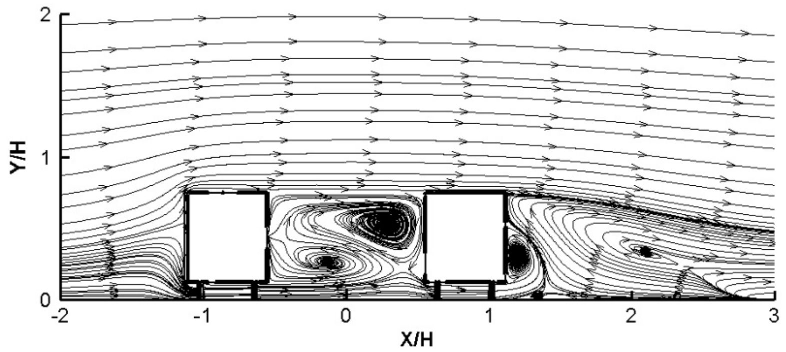


Fig. 15. Wind flow pattern of the "U" shaped building with streamlines under the parallel wind direction on the x-z plane at $y/H = 0$.

The influence of lift-up design underneath the "U" shaped building on its neighbouring places is given quantitatively in Fig. 16. By comparing the ΔMVR distributions under three wind directions in Fig. 16, it is clear that the values of MVR in the semi-closed zone increase most under the normal wind direction. Fig. 16(b) shows that under the oblique wind direction, the areas of MVR in the semi-closed zone decrease at the place behind the upstream building core when the lift-up design is used. It can be observed from Fig. 16(c) that the values of MVR in the semi-closed zone are partially increased under parallel wind direction, particularly at the place where the approaching flow and the downwash flow meet. Apart from this, there is an outstanding wind enhancement in ULWV zone and DNLWV zone under three wind directions. However, there is a noteworthy decrease in the DFLWV zone behind the building under the parallel wind direction. This can be explained by the counteraction between the horizontal wind flow and the reattachment flow of the vertical recirculation behind the building, as can be seen in Fig. 15.

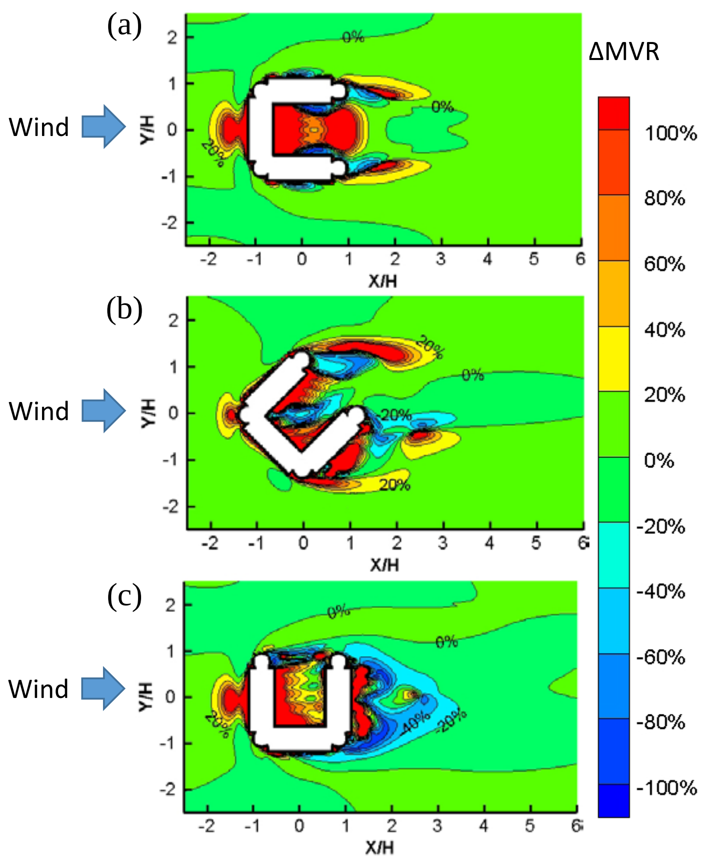


Fig. 16. Effects of lift-up design around the “U” shaped building at pedestrian level under three wind directions: (a) Normal wind (θ=0°); (b) Oblique wind (θ=45°); (c) Parallel wind (θ=90°).

4.4 The effects of lift-up design in the “□” shaped building

Fig. 17 illustrates the MVR distributions of the “□” shaped building at pedestrian level with lift-up design under three wind directions (normal and parallel wind directions are same here). The wind environments of LUWV zones under the normal or parallel wind directions are generally comfortable, as shown in Fig. 17(a). However, the values of MVR at the LUWV zones underneath the upstream block of the “□” shaped building are over 0.5 while below 0.4 underneath the downstream block. Fig. 17(b) demonstrates that the wind environments are comfortable in the LUWV zones under the oblique wind direction. Besides, the values of MVR are overall higher in the LUWV zone under the oblique wind direction than the other two wind directions.

The distinct feature of the "□" shaped building is the closed zone formed by the surrounding blocks. It can obtained from Fig. 17(a) that the wind environment of the closed zone is comfortable under the normal or parallel wind directions except at the place where the horizontal flow and downwash flow meet. Fig. 17(b) shows that the wind environments of the closed zones are comfortable in lateral places while uncomfortable in the middle place under the oblique wind direction. The uncomfortable area can be accounted for the shielding effect of the upstream building core.

It can also be found that the LHWV zones are comfortable for pedestrian activities under three wind directions. Besides, the values of MVR in the DNHWV zone under the oblique wind direction are higher than the other two wind directions. As for the ULWV zone, the wind environment is better under the oblique wind direction than the other two wind directions. Similar to the findings of the "U" shaped building, the values of MVR in the DFLWV zone are higher under the oblique wind direction than the other wind directions.

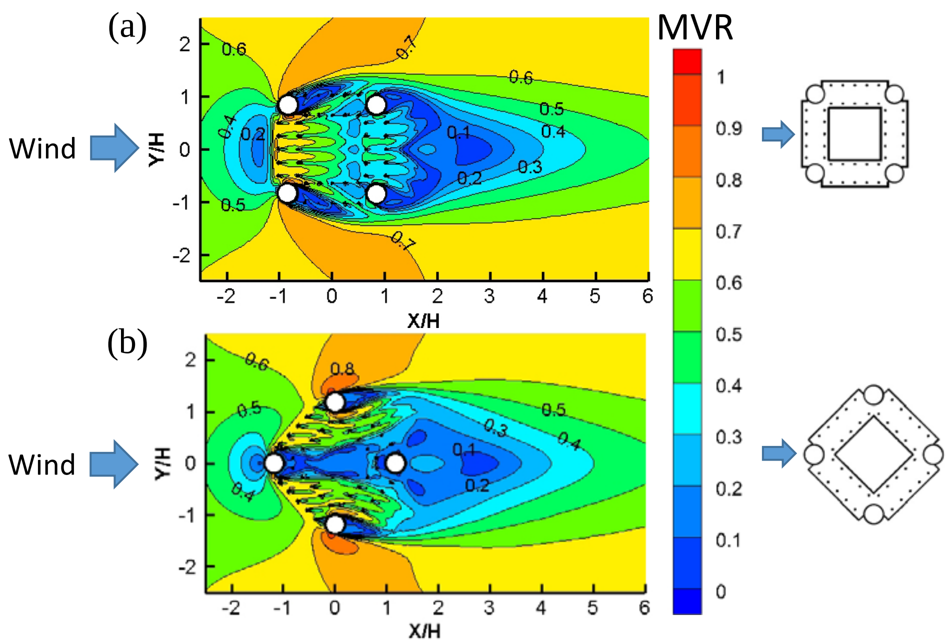


Fig. 17. MVR distributions around the "□" shaped building with lift-up design at pedestrian level under three wind directions: (a) Normal wind (θ=0°) and Parallel wind (θ=90°); (b) Oblique wind (θ=45°).

Fig. 18 presents the influence of lift-up design underneath the "□" shaped building on its neighbouring places quantitatively. For the closed zone, Fig. 18(a) shows that the values of MVR in the closed zone increase noticeably near the leeward face of the upstream block and windward face of the downstream block under the normal or parallel wind directions. However, the values of MVR in the closed zone increase greatly on the lateral sides while decrease in the middle place under the oblique wind direction, see Fig. 18(b).

It can also be observed from Fig. 18 that the closed zone, ULWV zone and DNLWV zone are affected by the lift-up design under three wind directions. The LHWV zones are insensitive to the lift-up design in the "□" shaped building under three wind directions. It is noticeable that the values of MVR in the DFLWV zone decrease under three wind directions because of the lift-up design. Moreover, the values of MVR in the DFLWV zone decrease more under the normal or parallel wind direction than that under the oblique wind directions.

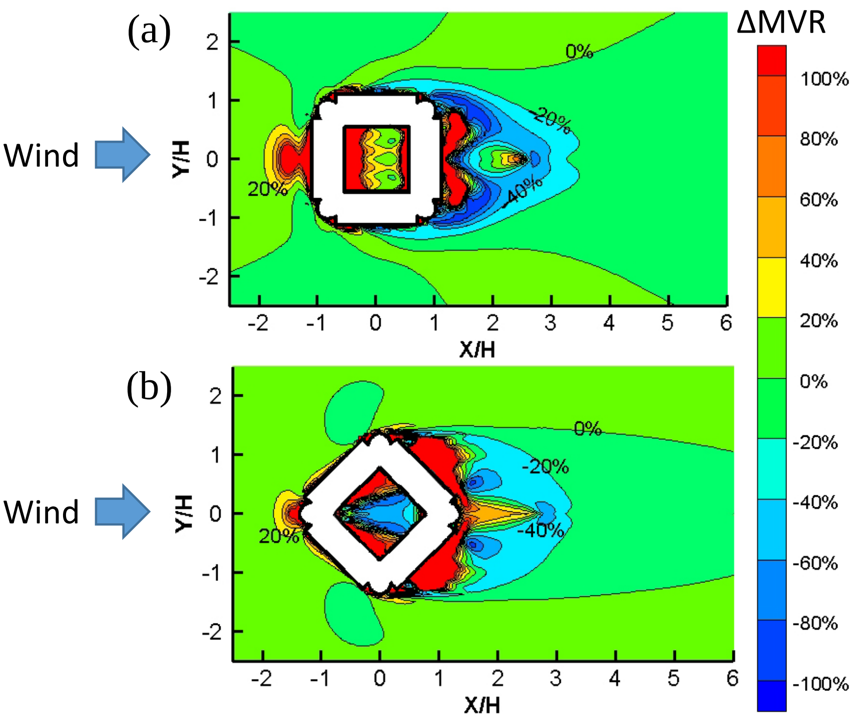


Fig. 18. Effects of lift-up design around the "□" shaped building at pedestrian level under three wind directions: (a) Normal wind (θ=0°) and Parallel wind (θ=90°); (b) Oblique wind (θ=45°).

4.5 Comparisons between different building configurations

The effects of lift-up design on the pedestrian level wind comfort around the four building configurations are similar: the lift-up design can only affect the LUWV zone and the neighbouring zones around the buildings. It can be summarized from the results that the LUWV zone is wind uncomfortable for pedestrian activities when the LUWV zone is parallel to the approaching wind, while the LUWV zone is wind comfortable for pedestrian activities when the LUWV zone is normal or oblique to the approaching wind. Besides, it can be obtained from the “U” shaped building and the “□” shaped building that when the paralleled two LUWV zones are normal to the approaching wind, the values of MVR underneath the upstream blocks are evidently larger than that underneath the downstream blocks. Besides, the wind environments of the semi-closed zone of the “U” shaped building and the closed zone of the “□” shaped building are generally favourable for pedestrian activities. However, there is a low wind velocity zone occurs at the location where the horizontal approaching wind and downwash flow meet in these two zones. In addition, the LHWV zones are wind comfortable in all the cases investigated in this paper, and the DNHWV zones are wind comfortable in most of the cases studied except the case when the “—” shaped building under the parallel wind direction. Furthermore, as for the low wind velocity zones, the ULWV zone and DFLWV zone are wind uncomfortable.

The results of MVR in the ULWV zone and DNHWV zone are significantly amplified by the lift-up design in all the cases studied, while the LHWV zones are insensitive to the lift-up design in all the cases. In addition, the values of MVR in the semi-closed zone of the “U” shaped building and the closed zone of the “□” shaped building are increased because of the lift-up design except for the regions behind the upstream building cores under the oblique wind direction. However, the values of MVR decrease in some places of the DFLWV zone when the lift-up design is adopted in the buildings.

Furthermore, the values of MVR in the DFLWV zone of the “□” shaped building reduce more than other building configurations when the lift-up design is used.

The results presented in the paper mainly focused on the pedestrian level wind environment around the four different building configurations. Further works will be carried out to investigate the other influencing factors, like the height of the lift-up design and so on. Besides, the results presented in this paper are based on the neutral atmospheric boundary layer and the weather conditions, like radiation and rain, will be considered in the future studies.

5. Conclusions

This study sets out to study the effects of the lift-up design on different building configurations. The lift-up design in the HKPloyU campus is selected as the study model and the wind flows around four common building configurations are investigated under three wind directions.

The pedestrian level wind comfort under weak wind conditions is evaluated based on the MVR distributions around buildings. The results show that the lift-up design helps in improving the pedestrian level wind comfort in the LUWV zone and the surrounding areas of the four building configurations. Besides, the LUWV zones present comfortable wind environment when the approaching wind is normal or oblique to the LUWV zone. Furthermore, the pedestrian level wind comfort of the four building configurations are better under the oblique wind direction than the other two wind directions in this study. As for the effects of the lift-up design, which are quantitatively assessed by employing ΔMVR, the results of MVR in the ULWV zone, LUWV zone and DNHWV zone are significantly amplified while the values in the LHWV zone change slightly when the lift-up design is used. However, the values of MVR in some places of the DFLWV zones are decreased due to the lift-up design.

The results presented in this work provide an insightful understanding of the effects of the lift-up design on pedestrian level wind comfort under weak wind condition. These findings can help the architects and urban planners to design better precinct hat can help in improving the pedestrian level wind comfort in the densely built-up urban cities.

Acknowledgement

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