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Particle image velocimetry measurement and CFD simulation of pedestrian level wind environment around U-type street canyon

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Abstract

The configuration of an urban street canyon plays an important role in determining local microclimate including pedestrian level wind environment (PLWE). The semi-closed U-type street canyon has been widely used in high-density trans-oriented-development urban design for providing private space. However, a quantitative evaluation on PLWE of the U-type street canyon is still absent to date. This study quantitatively assesses PLWE of the U-type canyon via particle image velocimetry tests in a wind tunnel. A range of canyon aspect ratios (the ratio of the canyon height to width) and length ratios (the ratio of the canyon length to height) were investigated. The wind flow inside and in the vicinity of the street canyons was measured and analysed under the perpendicular, oblique and parallel approaching wind directions. It was found that the U-type canyon shows a higher PLWE inside canyon on the open side while a lower PLWE inside canyon on the closed side. Compared to parallel canyon, there is a significant enhancement of PLWE in the centre of the U-type canyon and in some spots on the leeward side of the canyon. This is further strengthened with increasing the canyon aspect ratio and length ratio. Nevertheless, the U-type canyon

exhibits a lower wind speed at the pedestrian level than that of the parallel canyon both inside and in the vicinity of the street canyons in general especially under parallel wind direction. It is believed that these findings are greatly beneficial to build sustainable cities with a high quality PLWE.

Keywords: Pedestrian level wind environment, U-type street canyon, parallel street canyon, particle image velocimetry, wind tunnel test.

1. Introduction

In metropolitan cities, the rapid urbanization process has caused unsatisfactory urban ventilation and poor air quality [1-5]. Semi-enclosed spaces between the mid-to-high buildings, called street canyons, always have highly polluted areas because of the moderate airflow caused by the presence of surrounding buildings. In recent years, pedestrian level wind environment (PLWE) has received increasing attentions due to the fact that the successful achievement of acceptable PLWE is seriously hindered by tall and bulky buildings in the urban regions [6-11]. It was reported that the wind speed has lowered from 2.5 m/s to 1.5 m/s over 10 years based on the record of Hong Kong observatory at Tseung Kwan O in Hong Kong [12]. As a result, the cooling effect of wind flow that can contribute to the reduction of heat stress in urban cities is deteriorated, which increases the cities' chance of suffering from urban heat islands [13-16].

An acceptable PLWE is essential for residents living in a high-density city, and also important for building a sustainable city [17, 18]. It is certain that a clear understanding of PLWE of the high-density city is a preliminary step for improving it. Ng [19] reported the health and comfort problems caused by a feeble wind condition in Hong Kong, and the corresponding strategy of establishing the air ventilation assessment. The issues caused by a feeble wind condition in a high-density urban environment have also been identified by Ai and Mak [20], and Hang et al.[21, 22]. Later on, Du et al [23] proposed a new wind comfort criterion for evaluating the wind environment of Hong Kong, and a case study demonstrated that the new wind comfort criterion can effectively represent the feeble wind condition and identify the problematic area. In order to improve PLWE, the lift-up design, arcade deign, and different building distribution strategies have been adopted in building design [10,17]. Moreover, a general guideline for improving PLWE was developed by Du et al. [24], and a case study in Hong Kong was conducted to illustrate the validity of the guideline. In addition, an unfavourable PLWE caused by stagnant wind flow has been detected by them in Hong Kong, especially in deep street canyons.

The key factor that determines the airflow pattern around an isolated street canyon is the street aspect ratio (*H/W*), which is defined as the ratio of the canyon height (*H*) to the interval between two rows of buildings (*W*). Based on field measurements and mathematical models, Oke [25] defined three flow regimes according to the aspect ratio range: isolated roughness flow ($H/W < 0.3$), interference flow ($0.3 \leqslant H/W < 0.7$), and skimming flow ($H/W \geqslant 0.7$). Among these three flow regions, the skimming flow has the lowest wind speed at the pedestrian level because most of the airflow skims over the upstream building and forms a single vortex in the street canyon [26]. In the past few decades, numerous investigations have been carried out to study the wind environment inside the street canyon in urban areas [27-31]. The studies with respect to two-dimensional (2*D*) street canyon revealed that the ground level wind flow would be first mixed with the vortices in the street canyon and then travel out of the 2*D* street canyon from its roof. Some researchers reported that there is one main vortex as H/W=1, 2 or 3, but two vortexes as H/W=5 or 6 in full-scale 2*D* street canyons in which the pedestrian-level wind speed is much smaller [31]. However, the street canyon is three-dimensional (3*D*) in reality. The wind flow movement is similar to that in the 2*D* street canyon, and a coupling process between the wind flow inside the canyon and the upper wind flow will be established if the wind speed above the canyon is high enough. This coupling process is significantly weakened when the canyon aspect ratio is too large, which leads to a feeble wind environment at the pedestrian level. Based on on-site measurements, Andreou and Axarli [32] found that the wind speed inside the street canyon was higher with a lower aspect ratio, and the difference of the wind speed between the street with a low and high aspect ratio was increased as the ambient wind speed increases. In addition, both the street canyon configuration and the canyon length ratio (*L/H*) (the length of canyon (*L*) to the height of canyon) affect PLWE inside the street canyon.

Recently, small blocks created by dense vehicle road network is highly recommended for trans-oriented-development (TOD) urban design [33]. The small block usually has a canyon length ratio less than 5 (*L/H* <5), as shown in **Fig. 1**. The short street canyon of each small building block is the basic units of urban. Among all the building dispositions, it is very common to find buildings located at the ends of building communities because it can create private space in canyons of a building block (see **Fig. 2**). As a result, this creates many semi-closed U-type street canyons. It has been reported that a deep street canyon (*H/W*>1), especially the U-type canyon, can results in a feeble wind environment in high-density cities [34]. Unfortunately, the deep street canyon is very common in high-density cities, such as Hong Kong, Shenzhen, and Singapore. Intuitively, PLWE in the U-type street canyons should be very different from that in typical parallel street canyons. To date, PLWE in the vicinity of the U-types street canyons remains unknown. Differences of PLWE between the U-type street canyon and the typical parallel street canyon with different aspect ratios and length ratios have also not been studied. Thus, it is worthy of a comprehensive investigation on PLWE of the U-type canyon and differences between the U-type street canyon and the typical parallel street canyon.

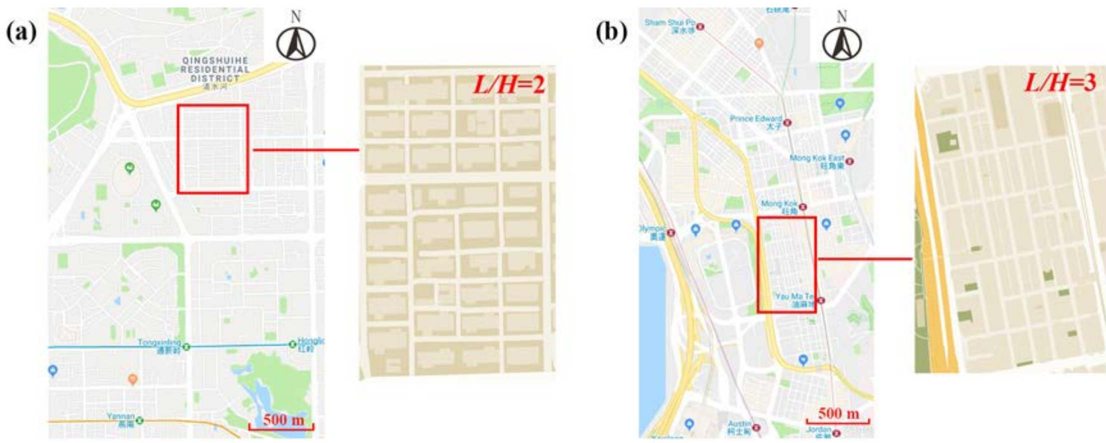

Fig. 1 Map of small blocks in TOD design of (a) Shenzhen and (b) Hong Kong.

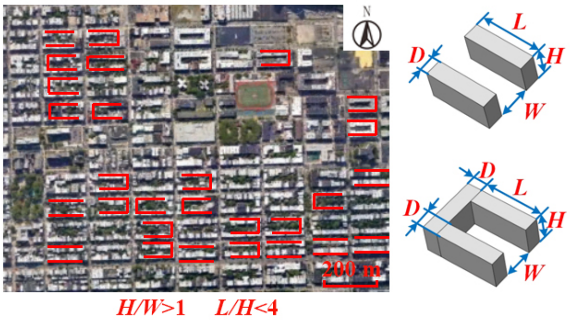

Fig. 2 Configuration of street canyon in TOD city.

This study aims to investigate influences of the U-type canyon in the high-density TOD urban design on PLWE under weak wind condition. Particle image velocimetry (PIV) technique was utilized to visualize the flow field in the vicinity of the parallel and U-type street canyons with different *H/W* and *L/H* ratios in the wind tunnel. Firstly, PLWEs of the U-type and parallel street canyons were evaluated, and then differences between the U-type and its corresponding parallel street canyon were quantified. The remainder of this paper is organized as follows: after the introduction, Section 2 describes the configuration of the test models. The detailed description of experimental setup is presented in Section 3. and the evaluation parameters are stated in Section 4. The results and discussions are shown in Section 5. Finally, concluding remarks are given in Section 6.

2. Test model description

To evaluate pedestrian level wind environment (PLWE) of the U-type canyon, two groups of canyon models: parallel canyons and U-type canyons, were tested. The approaching wind is perpendicular to the street canyon test models. The schematic diagrams of the parallel and U-type canyons are shown in **Fig. 3**. The test models in this study was designed based on a block building with full-scale dimensions of 60 m × 15 m × 30 m in length (*L*), depth (*D*), and height (*H*), respectively. The full-scale width (*W*) between the two parallel buildings is 30 m. According to previous research [28], deep canyons (height/width aspect ratio larger than 1) has the worst pedestrian level wind environment. The canyons are usually lager than 1. Thus, this study considers two height/width aspect ratio 1 and 2. The buildings in parallel have the same dimension for both the parallel canyon and U-type canyon. Based on the basic case, the test models were modified by increasing the length and height of the parallel buildings (see **Fig. 3**). The detailed dimensions for the eight cases are listed in **Table 1**.

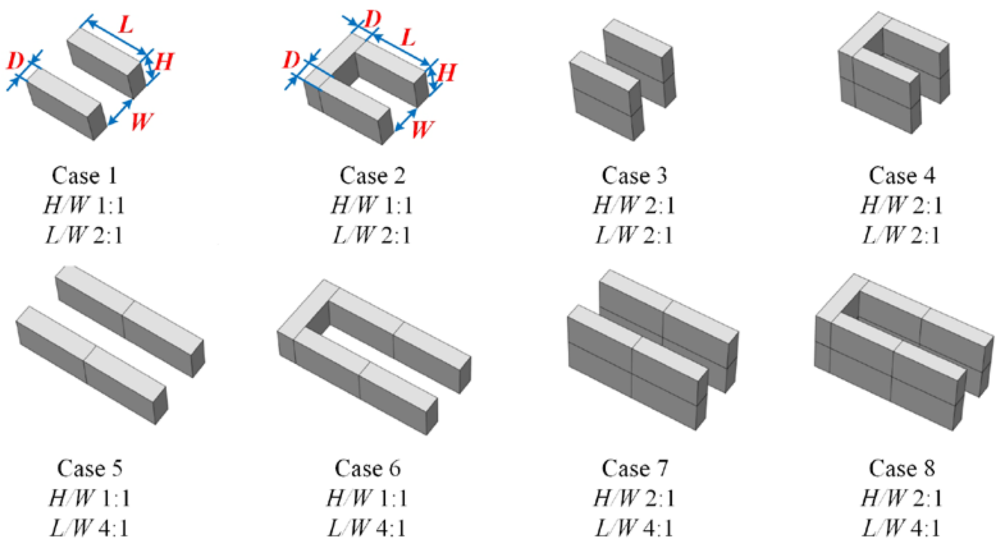

Fig. 3 Tested street canyon models in wind tunnel.

Table 1. Building dimensions (in full-scale) for the eight cases

Cases	Length (*L*, m)	Depth (*D*, m)	Height (*H*, m)	Width (*W*, m)	Aspect ratio	Length ratio
1	60	15	30	30	1:1	2:1
2	60	15	30	30	1:1	2:1
3	60	15	60	30	2:1	2:1
4	60	15	60	30	2:1	2:1
5	120	15	30	30	1:1	4:1
6	120	15	30	30	1:1	4:1
7	120	15	60	30	2:1	4:1

8	120	15	60	30	2:1	4:1

3. Experimental setup

Wind tunnel tests were conducted in the CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology. WWTF is a closed-return type subsonic boundary layer wind tunnel with two different test sections: high-speed test section and low-speed test section. The wind tunnel tests were carried out in the high-speed test section, which has a working section of 3 m × 2 m and a fetch length of 29.2 m. The test models were mounted on a flat plate with black paint for the purpose of diminishing the laser reflection. The height of the plate surface from the wind tunnel floor was 11 mm (see **Fig. 4 (a)**), which creates enough room to set up the laser head for measuring the flow field in the pedestrian level. The distances from the test models to the upstream, downstream, and lateral edge of the horizontal plate were 7.5 *H*, 12.25 *H* and 5 *H*, respectively.

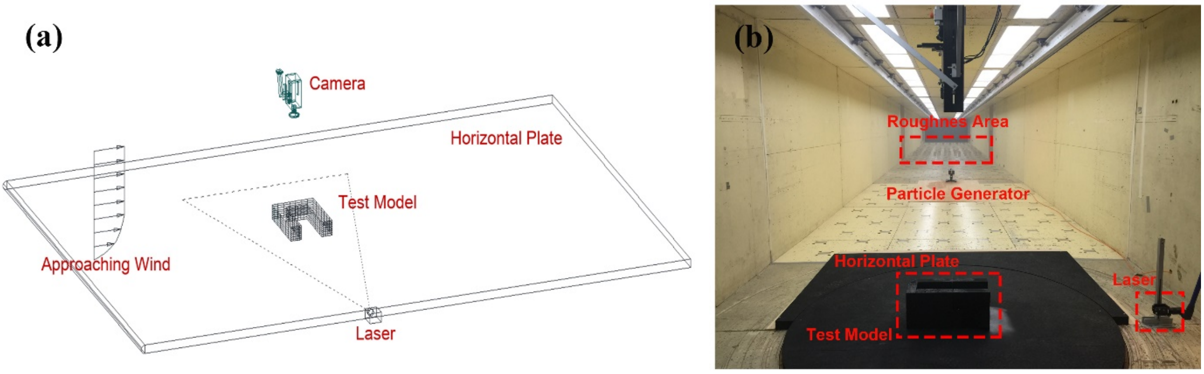

Fig. 4 Wind tunnel test: (a) Test model with PIV system; and (b) Test photo.

The test models were scaled and fabricated at a length ratio of 1:300. The blockage ratio for all the tested cases was much less than 5%, the threshold of the blockage effect [35, 36]. The Reynolds Number (*Re*) was over 15000, which was large enough to achieve Re independence for such kind of models with sharp corners [37]. The character length scale and wind speed when calculating *Re* are *H* (building height) and the wind speed at the reference point. The approaching wind profile was generated by the roughness elements in the upstream, as shown in **Fig. 4 (b)**. The mean wind speed profile followed a power law with an exponent of 0.2, which matches with that of an urban boundary condition, i.e. Terrain Category 2, specified in Australian/New Zealand Standard, AS.NZS 1170.2 [38]. The approaching wind profiles, including the mean wind speed profile and turbulence intensity profile, are shown in **Fig. 5**.

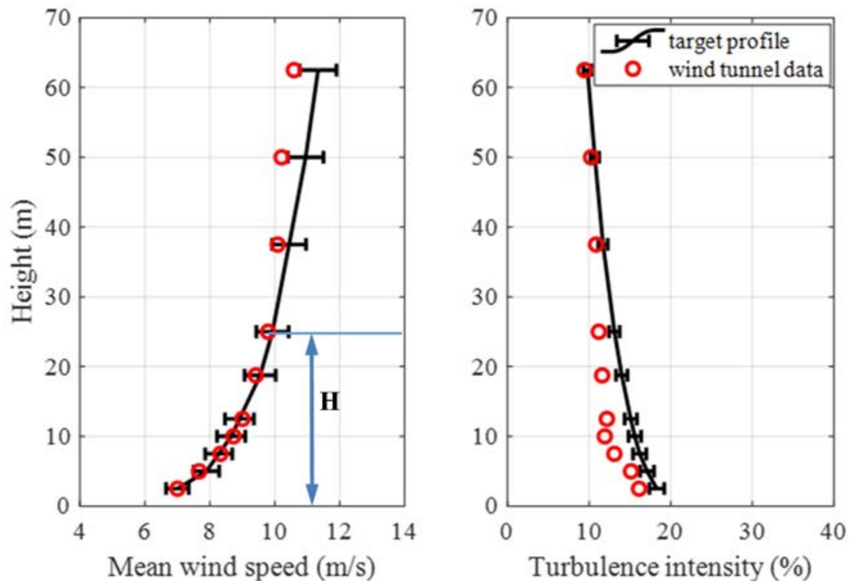

Fig. 5 Mean wind speed and turbulence intensity profiles (Error bars of 5% are provided).

The flow field was measured by using a *LaVision* standard PIV system. The measurements were taken along a horizontal plane at the height of pedestrian level. The plane was illuminated by a thin laser sheet generated from the laser beam of a dual cavity solid-state laser (Nd: YAG PIV Laser NanoTRL). Di-Ethyl-Hexyl-Sebacate (DEHS) fluid provided by *LaVision* was used to produce a fog of seeding particles using an aerosol generator. Flow images were captured by a high-speed CCD camera (Imager LX 11M), for which the pixel size is 9 × 9 μm^2 and the resolution is 4032 pixel × 2688 pixel. The framing speed was set at 2 double-image per second to capture a time sequence of particle images with a total number of 1000 of images. The time interval in the double pluses was set at 100 μs. The flow vectors were obtained on interrogation areas of size 32 × 32 pixels and with a 50% overlap. The final spatial resolution of the vector fields is 144 × 144 μm^2.

4. Evaluation parameter

The mean wind speed was used in this study to assess pedestrian level wind environment (PLWE) [39]. Specifically, the normalized mean wind speed known as mean wind speed ratio (MR) was utilized in this study, which enables the findings universal. In addition, a quality wind tunnel test is able to ensure the MR values in a scaled model to be identical to those in the corresponding in-situ condition [40]. Therefore, based on MR and the local meteorological wind statistics, the architect and urban planners can obtain the corresponding wind speed. The definition of MR is given as follows:

$$\mathrm{MR} = U_{ped}/U_{ref} \tag{1}$$

where U_{ped} is computed from root mean value of transversal and longitudinal velocity which wind speed at a specific spot at the pedestrian level; and U_{ref} stands for the wind speed at reference height at the inlet, here, 60 m in full-scale.

To quantitatively evaluate PLWE of the U-type canyon, the normalized difference of MR values (*K*) is used. This is obtained by the following procedures: first, PLWE around two canyons (parallel and U-type canyons) are studied and their respective MR values are obtained. The *K* value of the two canyons is then calculated by the following equation:

$$K = (MR_u - MR_P)/MR_P \tag{2}$$

where the subscript u represents the U-type canyon, and P denotes the parallel canyon.

The wind comfort criteria proposed by Du et al. [23] was used in the present study, since it has presented promising assessment results in low wind speed conditions. Meanwhile, only the wind comfort criterion of the hot season was considered in the present study, because the hot season is more critical than the temperate cold season for subtropical cities. In general, PLWE is acceptable when the wind speed is within the range from 1.5 m/s to 5.3 m/s in the wind comfort criterion for hot season [11, 17]. Moreover, according to the Hong Kong Planning Department, the mean wind speed is 5 m/s in summer at the reference height [41]. Thus, the wind comfort is considered as acceptable when MR values are between 0.3 (1.5/5) and 1.06 (5.3/5) in this study. This also corresponds with the air ventilation assessment (AVA) scheme established by Hong Kong government. In addition, since wind flow is desirable at pedestrian level in hot and humid Hong Kong, a higher value of MR (in the range of 0.3 to 1.06) is considered as more comfort.

5. Results and discussion

5.1 Wind flow vector

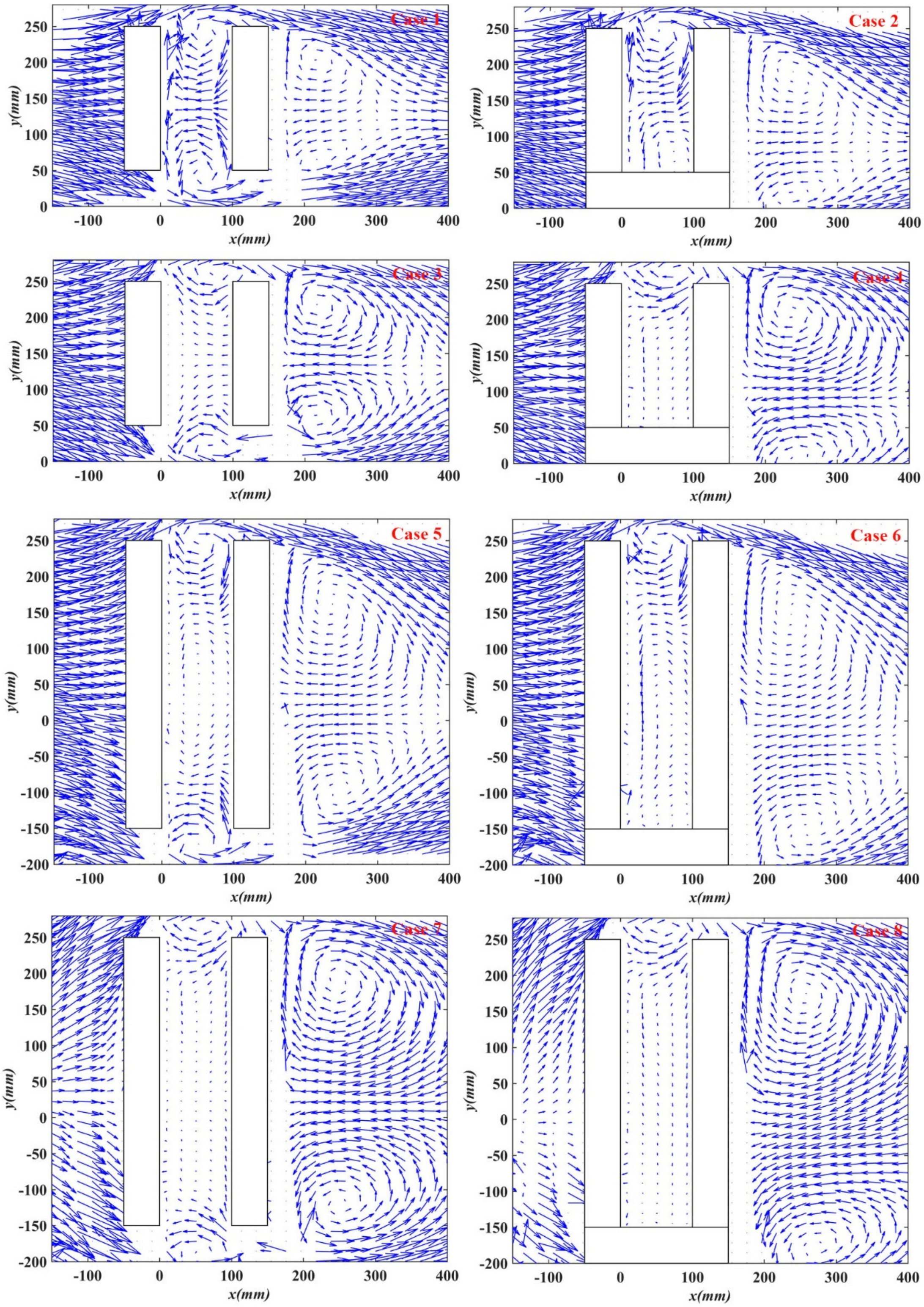

Fig. 6 Wind flow pattern with vectors at pedestrian level in the immediate vicinity.

One of the advantages of the PIV tests is that it can capture not only wind flow patterns but also wind speed. The mean wind flow vector fields in the immediate vicinity of the canyons for eight cases are shown in **Fig. 6**. It should be mentioned that the length of the vector is proportional to the magnitude of wind speed. Apparently, two symmetrical vortices are observed on the lateral sides of the parallel canyons due to the geometrical symmetry, whereas only one vortex is observed on the opening side of the U-type canyon. Another small vortex can be found on the closed side of the U-type canyon near the downstream building, which indicates stagnant wind flow in this area.

For both the parallel and U-type canyons, the depth of lateral vortices inside the canyons become smaller as the aspect ratio and length ratio increases (the canyon become higher and longer). For the short canyons (e.g. Case 1 and Case 2, Case 3 and Case 4), the vortices in the leeward side of the downstream building for the U-type canyon are bigger than those for the parallel canyon. However, for the long canyons (e.g. Case 5 and Case 6, Case 7 and Case 8), the difference of these vortices in the U-type canyon and the parallel canyon is negligible. Apparently, for the short canyons, the flow pattern of the U-type one is very different from that of the parallel one. Therefore, special attention should be paid when adopting U-type for short canyon. Meanwhile, the vortices in the leeward side of the canyons have no obvious changes as the aspect ratio increases for both the parallel and U-type canyon. For parallel canyons, the MR values along with canyons are symmetric inside canyons, the lowest MR area occurs in the central of canyons. For U-type canyon, the MR values along with canyons firstly increase and reach the high peak at 25% away for the bottom "U" of the canyon. The MR values along with canyons then decrease and reach low peak value where are 60% of canyon length away from the bottom "U" of the canyon. The mean wind speed is adopted when assessing pedestrian level wind comfort.

5.2 Wind environment assessment

The distributions of MR values in the immediate vicinity of the parallel canyon and U-type canyon are displayed in **Fig. 7**. As illustrated in **Fig. 7**, the pedestrian level wind environment around the U-type canyon is quite different from the wind field of the parallel canyon. The most noticeable difference can be found in the inside space, known as low wind speed (LWS) zone, in which the skimming flow at the pedestrian level in the U-type canyon is lower in magnitude than the parallel canyon. A LWS zone is presented in the upstream area of both the parallel canyon and U-type canyon (hereafter referred as UNLWS). For the parallel canyon, the high wind speed (HWS) zones are formed on both lateral sides because of the geometrical symmetry. However, a LWS zone is formed on the closed side of the U-type canyon while a HWS zone is formed on the bottom of the canyon. A downstream near-field low wind speed (DNLWS) zone can be observed for both canyons. Because of the limited measuring area of the PIV tests, the influence of canyon configuration on downstream far-side wind speed is not available. Moreover, it is obvious that the MR values in most areas is below 0.1, which can be considered as very LWS areas. These areas should be paid more attention since very LWS areas can result in poor air ventilation and cause outdoor thermal comfort issues in subtropical cities. Besides, very LWS areas can lead to accumulation of airborne pollutants in high-density cities. In general, the MR values at pedestrian level of Case 1 are higher than those of Case 2. As declared in the previous section, the wind environment is unfavourable when the MR value is below 0.3. Thus, the wind comfort is unfavourable in ULWS zone, LWS zone inside the canyon, and DNLWS zone for Case 1 and Case 2.

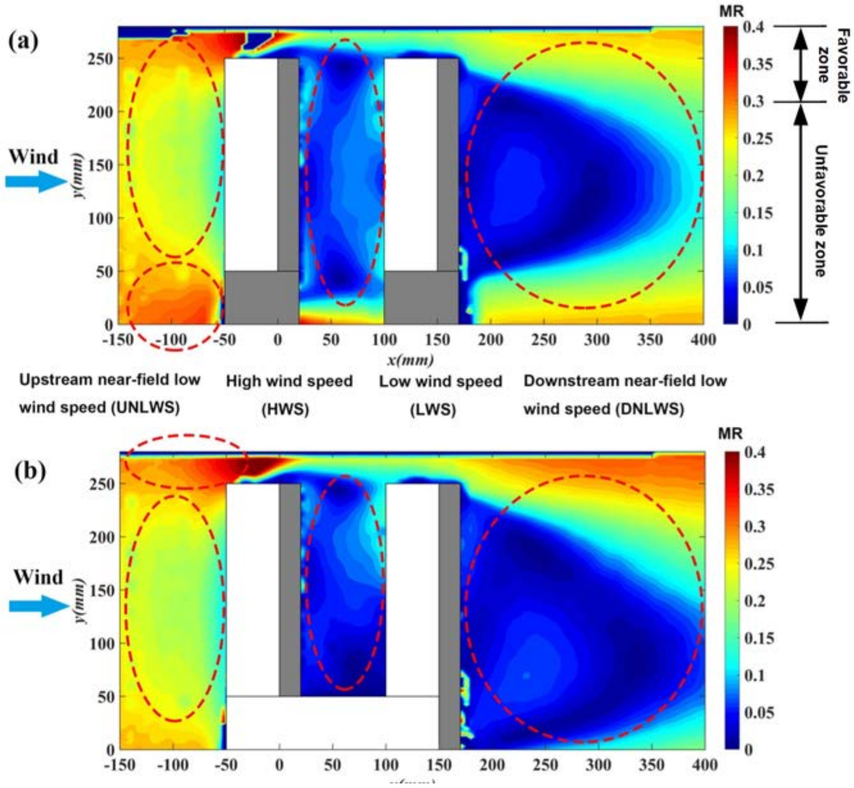

Fig. 7 Distributions of MR in the immediate vicinity of canyons (a) Case 1 and (b) Case 2.

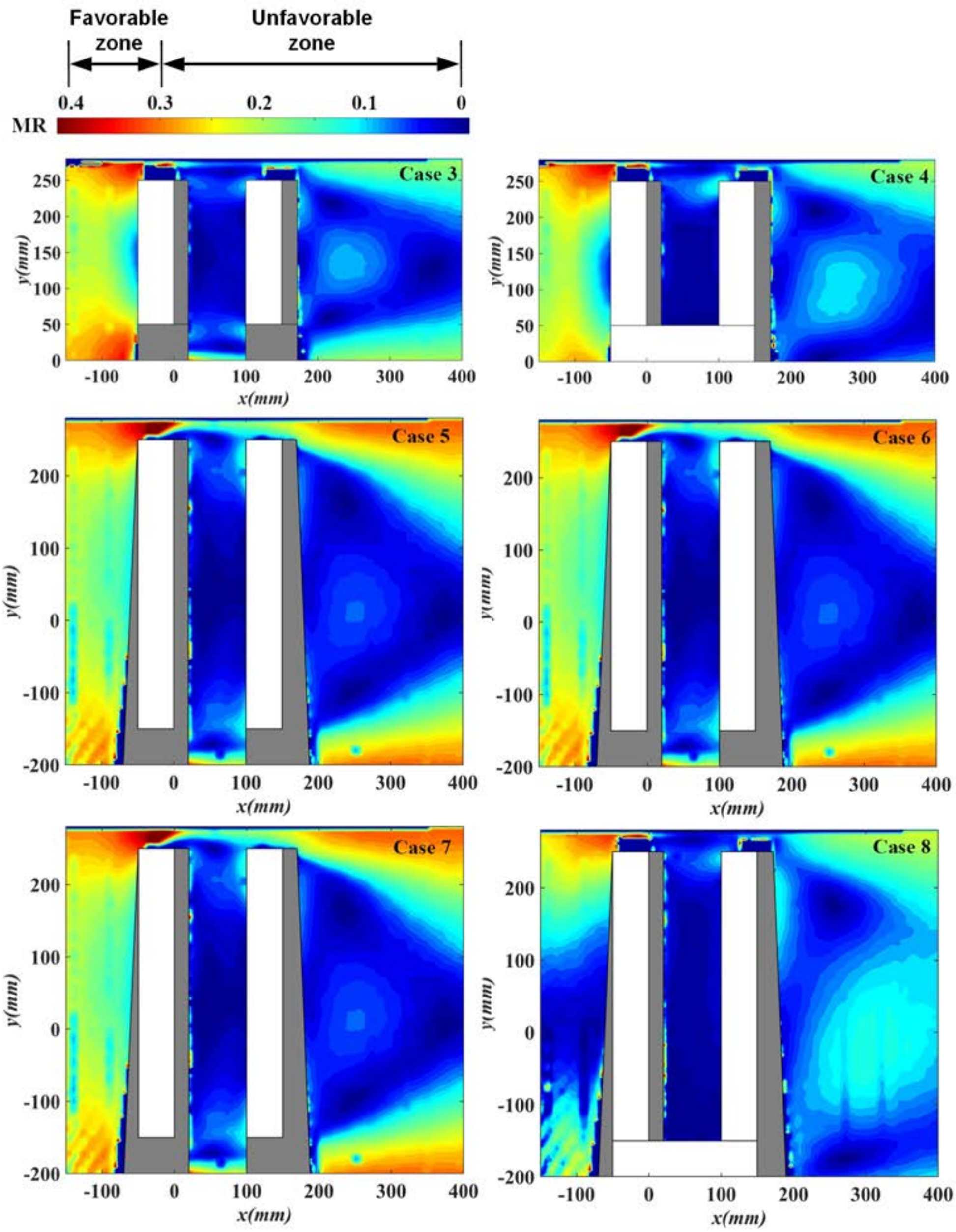

Fig. 8 Distributions of MR in the immediate vicinities of 6 cases.

Fig. 8 presents how the wind environment at the pedestrian level in the vicinity of canyons varies with the length and height of the parallel and U-type canyon. Generally, the pedestrian level wind environment (PLWE) of all eight cases exhibits low wind-speed features, and the wind comfort is unfavourable for any pedestrian activities in ULWS zone, LWS zone inside the canyon, and DNLWS zone. More specifically, the low pedestrian wind field in the vicinity of U-type canyon is lower in magnitude and larger in size than that of parallel canyon. However, the wind speed magnitude of very LWS area in DNLWS zone of the U-type canyon is higher than that of the parallel canyon because of stronger backflow in the leeward side of the U-type canyon. Moreover, the wind speed magnitude of very LWS area inside the canyons of the U-type is lower than that of the parallel canyons.

As the length ratio and aspect ratio increases, the wind speed magnitude of pedestrian wind flow in the ULWS zone is decreased and the size of very LWS area (MR < 0.1) is increased. Besides, the wind speed in the LWS zone inside the canyon is decreased as the length ratio and aspect ratio increases. Further, the magnitude of very low areas in the DNLWS zone is decreased and the size of this very LWS areas is increased as the length ratio increases. However, the magnitude of this very LWS area is increased as the aspect ratio increases because of stronger backflow in the leeward side of the canyon. For low length ratio canyons (Case 1 to 4), the magnitude of corner flow on the lateral opening side of the U-type canyon near the downstream building is higher than that of the parallel canyon. However, these corner flows are similar for the U-type and parallel canyons when the length ratios high.

5.3 Normalised difference between two canyon types

To quantitatively evaluate effect of the U-type canyon, the distributions of calculated *K* values (defined in Section 4) are presented in **Fig. 9**. The negative *K* values indicates that the U-type canyon results in lower wind speed than that of the parallel canyon. It can be seen that extreme values ($K > 1$ or < -1) appear in all the figures in **Fig. 9**, which indicate remarkable differences between the parallel and U-type canyons.

For the UNLWS zone, most of the *K* values in **Fig. 9** are negative, indicating that the wind speeds at pedestrian level around the U-type canyon are lower than those of the parallel canyon in UNLWS zones. As shown in **Fig. 9 (a)** and **(b)**, most of the *K* values inside the canyons are negative, and the magnitude of *K* values in **Fig. 9 (b)** is lower than that in **Fig. 9 (a)**. However, there are a number of large *K* values ($K > 1$) shown in **Fig. 9 (b)**, which indicates a significant enhancement in the wind speed at the pedestrian level. These extreme values can also be found in **Fig. 9 (c)** and **(d)**, and the size becomes larger as the aspect ratio and length ratio increases. Moreover, most of the *K* values in **Fig. 9 (c)** and **(d)** are positive, and the area of significant enhancement in **Fig. 9 (d)** (K > 1) is more than 50% of the canyon inside. This means that PLWE inside the canyon is higher for the U-type canyon than that of the parallel canyon, especially for the central part of the canyon inside. The additional building for U-type canyon have positive effect on increasing the central low wind speed area inside canyons because of backflow. However, the *K* values are negative near the lateral closed area of the canyon inside in **Fig. 9**. For the DNLWS zone, it is interesting to note that there are some areas with extreme high *K* values (*K* > 1) while the *K* values in other areas are negative. Moreover, the size of these high *K* values are reduced as the aspect ratio increases, which further confirms that a long U-type street canyon have a worse PLWE than that of a short U-type street canyon. However, the area with positive *K* values in the DNLWS zone increased as the aspect ratio increases due to stronger back flow in the leeward side of the canyon.

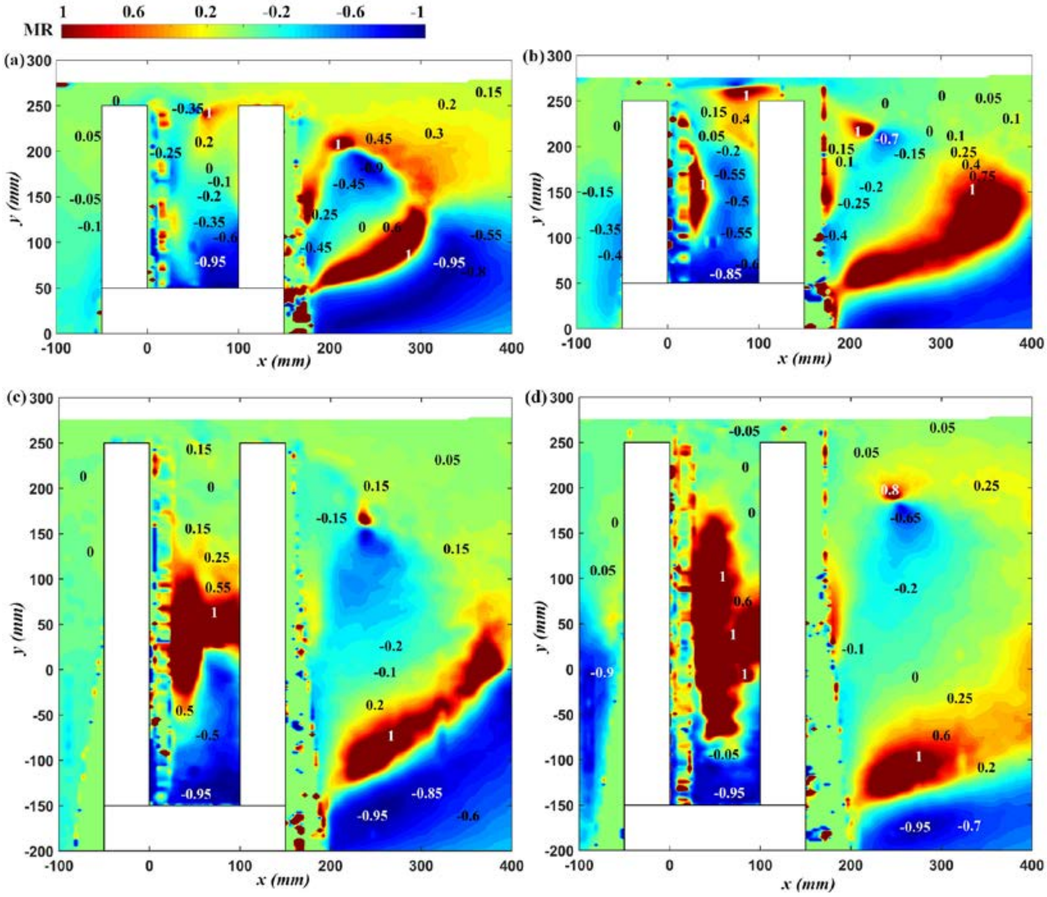

Fig. 9 Distributions of *K* values in the vicinity of the U-type canyon: (a) Case 2 and Case1; (b) Case 4 and Case 3; (c) Case 6 and Case 5; (d) Case 8 and Case 7.

5.4 Wind speed variation

To quantitatively show wind speed variation of the eight cases, **Fig. 10** presents the area percentage (AP) of various wind speed ranges for the measured regions. AP is the ratio of areas with a particular wind speed range to the whole measured area. As demonstrated in Section 4, the pedestrian level wind comfort is acceptable when the MR value is in the range of 0.3 to 1.06. It can be seen that most of the MR values are below 0.3, which means that most areas within the measured region is unfavourable for wind comfort. The parallel canyon has higher MR values than the U-type canyon in general. Particularly, the parallel canyon has lower AP values for MR<0.1 than that of the U-type canyon with same aspect ratio and length ratio. However, there is slight difference of the AP values when the MR is larger than 0.3 between the parallel and U-type canyon with same aspect ratio and length ratio. This means that the influence of U-type canyon is more on very LWS area than that of HWS area. For both the parallel and U-type canyons, the LWS area increases and the HWS area decreases as the aspect ratio and length ratio increase.

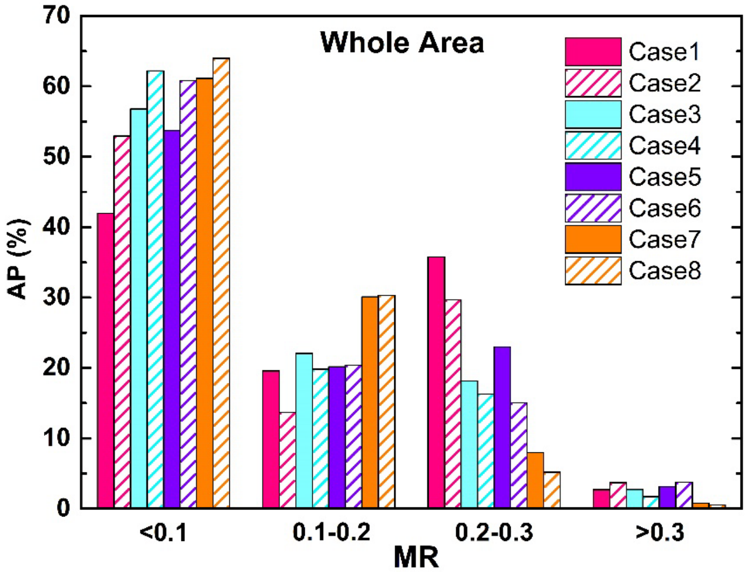

Fig. 10 Distributions of MR value with corresponding area percentage (AP) for whole measured area. (The filled bars mean parallel canyon, pattern bars mean U-type canyon)

The distribution of MR value with corresponding AP for UNLWS zone is shown in **Fig. 11**. It can be seen that the AP value of very LWS (MR < 0.1) is very low, except for Case 7 and Case 8 with high aspect ratio and high length ratio. Besides, the AP value of HWS (MR > 0.3) is higher for the parallel canyon than that of the U-type canyon. For both the parallel and U-type canyons, the AP value of HWS increases slightly as the aspect ratio increase, while it decreases as the length ratio increases. This is due to the fact that a stronger downwash flow in the windward face of the urban canyon is generated with higher aspect ratio. The AP values between 0.2 and 0.3 in relatively HWS areas decrease as the aspect ratio and length ratio increases for both the parallel and U-type canyons.

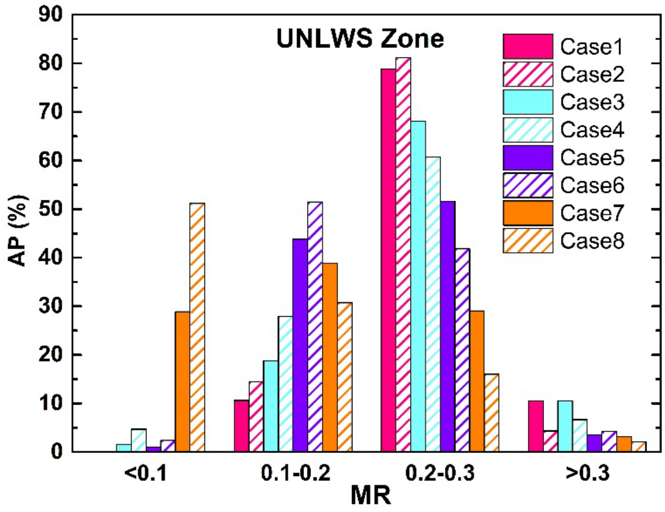

Fig. 11 Distributions of MR value with corresponding area percentage (AP) for UNLWS zone. (The filled bars mean parallel canyon, pattern bars mean U- type canyon)

The distribution of MR value with corresponding AP for the canyon inner zone is shown in **Fig.12** It is obvious that most of the AP values are below 0.1, which indicates unfavourable wind comfort and very poor ventilation condition inside the canyons both for the parallel and U-type canyon. However, the AP values of very LWS are slightly lower for the U-type canyon than that of the parallel canyon. This means that the U-type canyon can improve the very LWS condition inside the urban canyon. Besides, the AP value of very LWS increases as the length ratio and aspect ratio increases.

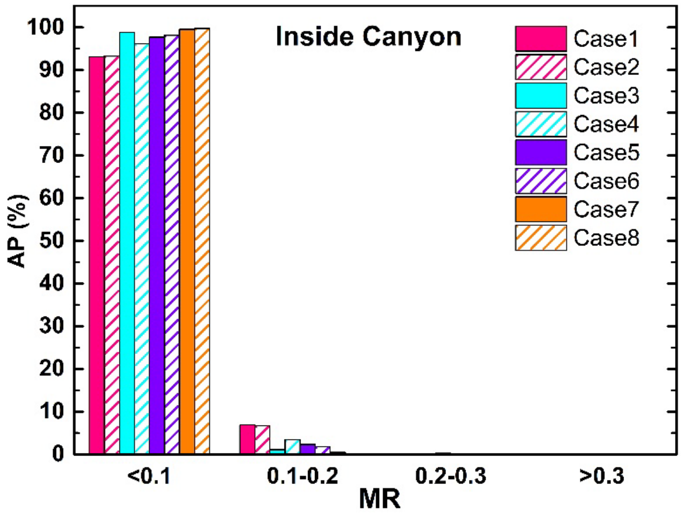

Fig. 12 Distributions of MR value with corresponding area percentage (AP) for inside canyon zone. (The filled bars mean parallel canyon, pattern bars mean U- type canyon)

Fig. 13 displays the distribution of MR value with corresponding area percentage (AP) for DNLWS zone. It can be seen that the AP value of the U-type canyon is higher for very LWS region (MR < 0.1) than that of the parallel canyon. This means that adopting U-type canyon can increase the area of very LWS region. However, the AP value of the U-type canyon is slightly higher than that of the parallel canyon for HWS region (MR > 0.3) when the canyons has low length ratio (short canyon).

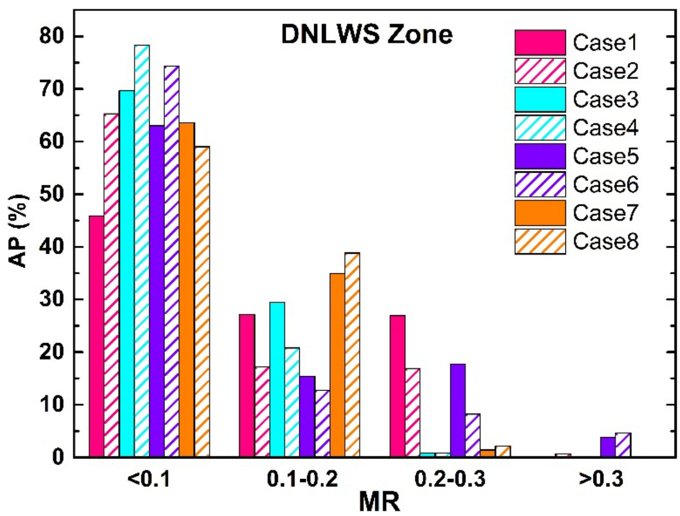

Fig. 13 Distributions of MR value with corresponding area percentage (AP) for DNLWS zone. (The filled bars mean parallel canyons, pattern bars mean U- type canyons)

5.5 Wind incidence angle effect on PLWE of canyons

In this section, influences of different incident wind directions on PLWE of the parallel and U-type canyon are evaluated by using Computational Fluid Dynamics simulations.

5.5.1 CFD methods and Validation

The velocity profile and turbulence profile used in the CFD simulations were identical to those in the wind tunnel tests (Case 1). Assuming that the flow is fully developed at the domain outlet, which means zero normal gradients and zero background pressure, the "pressure outlet" was selected. For the domain top and lateral sides, slip boundary conditions were adopted. Based on the best practice guidelines proposed by Franke et al.[42], a computational domain with an upstream distance of 5*H*, downstream distance of 15*H*, lateral distance of 5*H*, and height of 6*H* was chosen. A mesh scheme with 2.08 million cells consists of a hybrid grid with prismatic and hexahedral cells (see Fig.14).

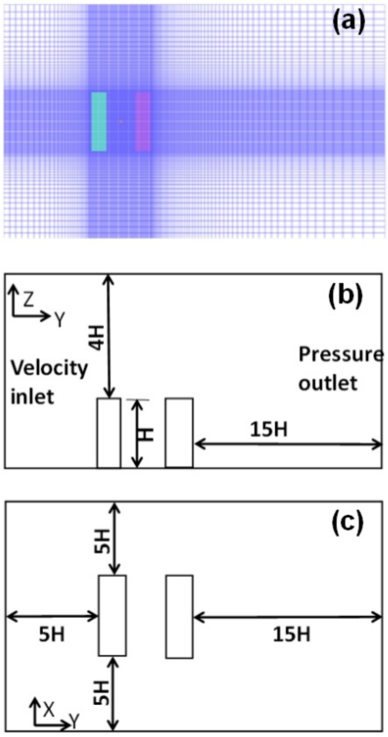

Fig. 14 Mesh and computation domain of validation Case 1

A mesh scheme with 3.5 million cells was employed after a similar mesh sensitivity test as described in the validation section. Three types of meshes, namely coarser, medium and finer, were constructed for Case 1 (1*H* 1*L* parallel street canyon), which contains 2.1 million, 3.5 million and 4.5 million cells, respectively. Wind pressure values on upstream building windward facade were predicted by the medium mesh are very close to those predicted by the finer mesh, with a deviation less than 5%. Compromising between numerical cost and accuracy, the medium mesh was employed in this study and further simulations.

Table 2 Boundary conditions for atmosphere boundary layer (ABL)

	Power-law type (validation work)
Domain inlet	$U = U_H \left(\frac{z}{z_H}\right)^{\alpha} \quad k = \frac{3}{2}\,(uI)^2 \quad \varepsilon = c_\mu k^{3/2}/l$
Domain outlet	$\frac{\partial}{\partial x}(u, v, w, k, \varepsilon) = 0$

Domain ceiling	$w = 0, \quad \frac{\partial}{\partial z}(u, v, k, \varepsilon) = 0$
Domain lateral sides	$v = 0, \ \frac{\partial}{\partial z}(u, w, k, \varepsilon) = 0$
Domain ground	Enhanced wall functions (near wall $y^{+} < 5$)
Building surfaces	non-slip for wall shear stress
Turbulence coefficients	$C_{\mu} = 0.085, \quad \eta_0 = 4.38, \ \beta = 0.015, \ \kappa = 0.42,$ E=8.331,

Table 2 summarizes the boundary conditions used in the present validation study. Note that similar boundary conditions were used in previous studies [29, 43-44]. The same velocity different turbulence boundary profiles were used in the CFD works of the experimenters. Convergence is assumed to obtain when all the scaled residuals level off and reach a minimum of 10-6 for x, y, z momentum, and 10-5 for k, ε, and continuity. As shown in Fig 15, three lines was selected to assess the accuracy of CFD prediction. The trends of CFD and PIV meets agreeable and the deviation smaller than 23% which is acceptable. Same boundary and mesh were employed in the following simulations.

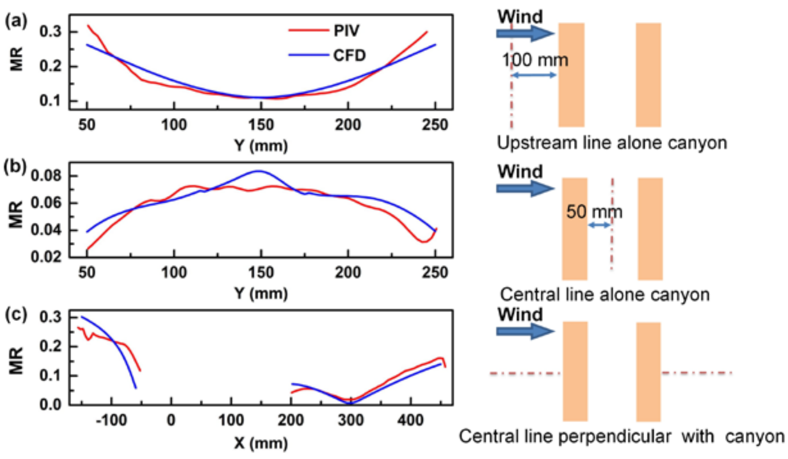

Fig. 15 PIV and CFD results of Case 1

5.5.2 Wind environment under oblique and parallel wind directions of 8 cases

The distributions of MR values in the immediate vicinity of the parallel canyon and U-type canyon under oblique incident wind direction are showed in Fig. 16. In general, the pedestrian level wind environment (PLWE) of all eight cases are unfavorable for pedestrian activities (MR<0.3) except for few spots near the corner of downstream building. The PLWE inside the U-type canyon is lower than that of the parallel canyon for the eight cases. For the two different length ratios, the PLWE in the immediate vicinities of the street canyon becomes lower as the building height increases. This is especially obvious for high length ratio.

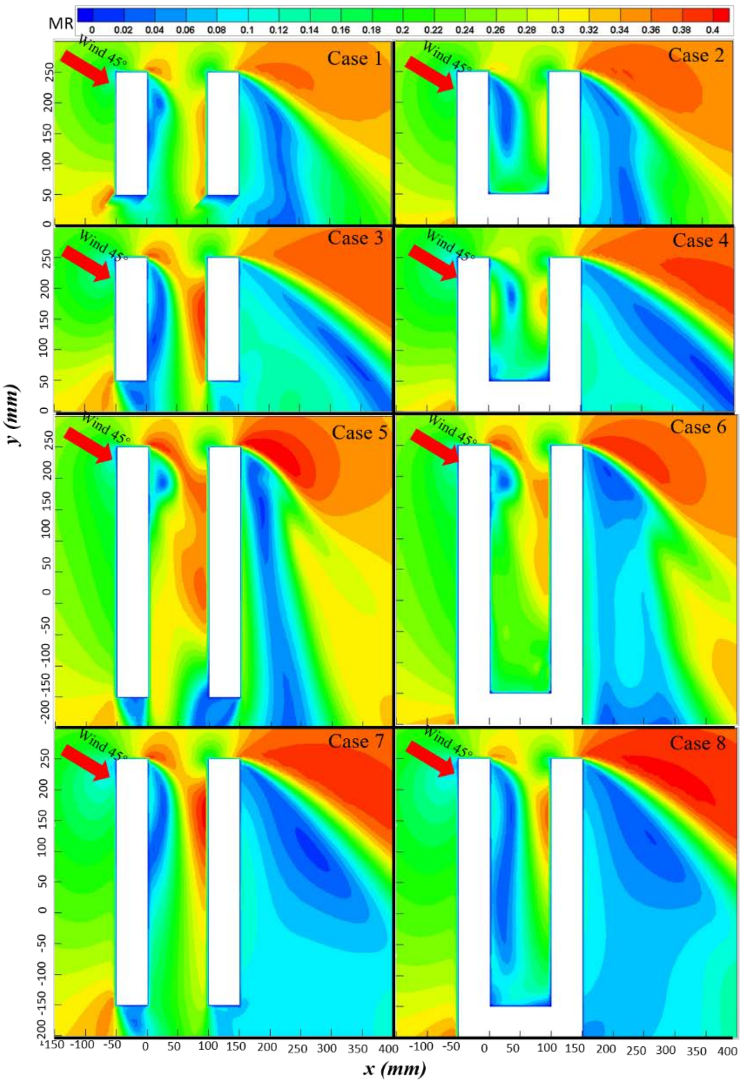

Fig.16 Distributions of MR in the immediate vicinities under oblique incident wind direction.

The distributions of MR values in the immediate vicinity of the parallel canyon and U-type canyon under oblique incident wind are displayed in **Fig. 17**. It can be seen that the PLWE in the immediate vicinities is significantly improved under parallel incident wind direction that that under perpendicular and oblique incident wind direction. However, the PLWE is still unfavorable for pedestrian activities. Particularly, the MR values decrease as the aspect ratio and length ratio increase. The PLWE is higher for parallel canyon than that of U-type canyon both in the vicinity area and areas inside the canyons.

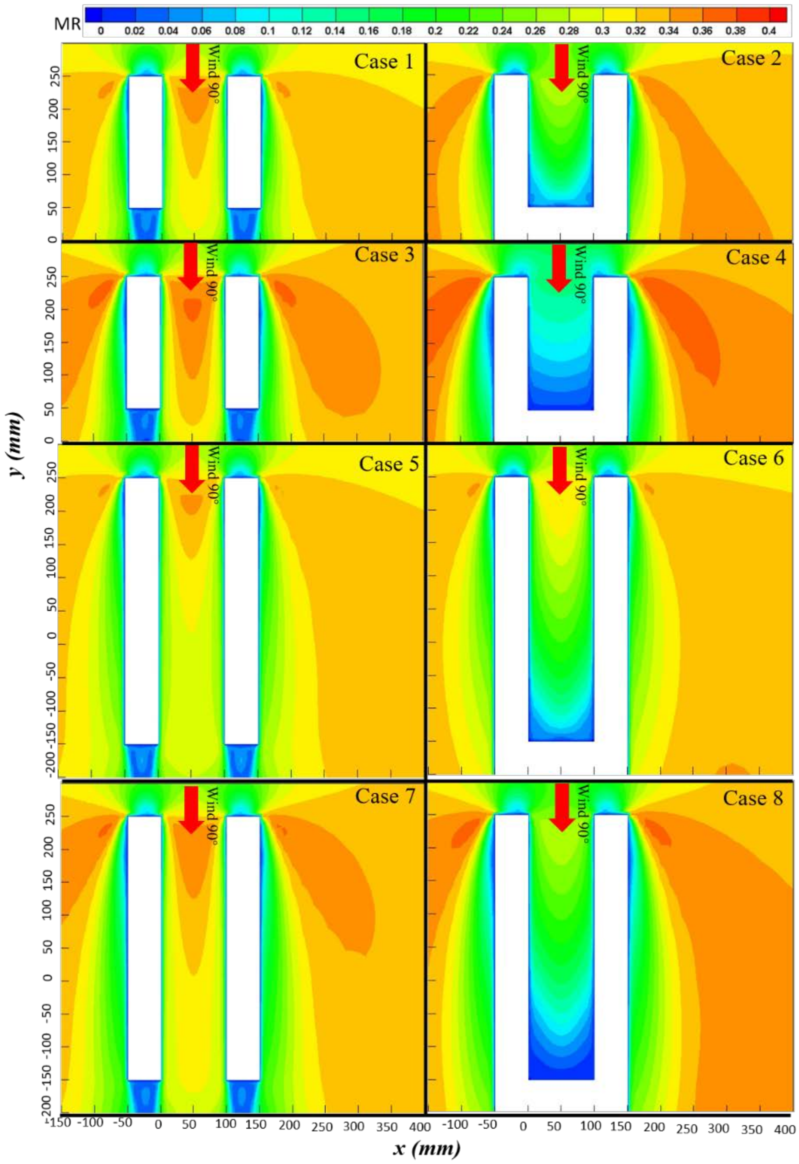

Fig.17 Distributions of MR in the immediate vicinities under parallel incident wind direction.

6. Discussion

This study focuses on generic canyon with different aspect ratio and wind directions (perpendicular, oblique and parallel). In real urban, the wind environment around canyon will be highly affect by surrounding building, in upstream, downstream and lateral stream [45-46]. For parallel canyons, the MR values along with canyons are symmetry inside canyons, the lowest MR area occurs in the central of canyons. For U-type canyon, the MR values along with canyons are asymmetry and the lowest MR area located in the bottom of the canyon. The mean wind speed is adopted when assessing pedestrian level wind comfort. However, for very low wind speed area around canyons, the turbulence transport term will have non-negligible contribution of turbulence to canyon ventilation. And this effect is worth to be taken account to improving wind comfort criteria for high density cities studies.

7. Conclusions

The pedestrian level wind environment in the immediate vicinity of the U-type canyon and its corresponding parallel canyon are studied in this paper using wind tunnel tests with PIV technique and CFD simulation. The approaching wind are perpendicular, oblique and parallel to the street canyon test models. The cases with two aspect ratios (one and two) and two length ratios (two and four) are investigated in this work, which represent deep and small blocks in high-density cities, respectively. The wind flow pattern, pedestrian wind comfort and wind environment are analysed comprehensively. The detailed findings are concluded as follows:

(a) The parallel canyon and U-type canyon both results in unfavourable pedestrian wind comfort in their immediate vicinity. This low wind condition become worse as the aspect ratio and length ratio increases.

(b) The wind flow structure in the leeward side of the canyon changes greatly when adopting U-type on short parallel canyon.

(c) By comparing the U-type canyon with the parallel canyon, the U-type canyon can result in lower wind environment at pedestrian level than that of the parallel canyon in general. However, the U-type canyon can improve pedestrian level wind environment on the centre part inside the canyon and some spots on the leeward side of the canyon, and the magnitude of this improvement increases as the aspect ratio and length ratio increases.

(d) The U-type canyon can be adopted in long street canyon for providing more dwelling space in high-density city, since the HWS regions does not decrease significantly and the wind speed inside the canyon increases when the U-type canyon is used. However, special attention should be paid when the short street adopts the U-type canyon.

(e) Under oblique wind direction, all inside canyon pedestrian level MR values are largest among three wind directions. Compared with parallel canyons, U-type canyons have lower inside canyon pedestrian MR value especially under parallel wind directions.

The above findings provide an insightful understanding of the effects of U-type canyon on pedestrian level wind environment under weak wind conditions. These findings can assist the city planners and policy-makers to design better district that helps in improving wind environment at pedestrian level for high-density cities. However, it has to be made clear that these conclusions were obtained with isolated street canyons.

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