The 2015 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM15)
Incheon, Korea, August 25-29, 2015

Characteristics of Pedestrian Level Wind Environment in Twisted Wind Flow around Isolated Buildings

* X. Zhang[1)] A.U. Weerasuriya[2)], K.T. Tse[3)] and K.C.S. Kwok[4)]

[1), 2)] Department of Civil and Environmental Engineering,
Hong Kong University of Science and Technology, Hong Kong, China
[3)] Institute for Infrastructure Engineering, University of Western Sydney, Penrith, NSW, 2751, Australia
[1)] xzhangbn@ust.hk

ABSTRACT

Air Ventilation Assessment (AVA) is the major investigation method to evaluate the impact of new development on existing pedestrian level wind environment in Hong Kong. The different stages of AVA employs wind tunnel tests to evaluate the approaching wind conditions and wind speed at the pedestrian level at the site of interest. However, the hilly terrain commonly found in Hong Kong induces uncertainties in AVA wind tunnel tests by generating twisted wind profiles. The twisted wind effect induced by the topography can be significant in assessing near ground wind environment. Therefore, influences of twisted wind profiles on the pedestrian-level wind environment were evaluated through a series of wind tunnel tests. Two twisted wind profiles, with a maximum twist angle of 13^o and 22^o were simulated in a boundary-layer wind tunnel. A conventional wind profile with zero twist was employed to repeat the wind tunnel test as a control case. More than 200 Irwin sensors were installed around five isolated building models to measure the wind speeds at pedestrian level at 10mm in model scale which equals to 2m in full scale. The dimensions of building models were selected to evaluate the influence of building height and building width on pedestrian level in presence of the twisted wind profiles. It was found that under the twisted wind profiles building far wake deviated from the along-wind axis and generated asymmetric corner streams in sides of the buildings. The wind environments generated by different wind profiles were quantitatively evaluated by using the velocity ratio (VR). By comparing the VR distributions under the influence of the two twisted profiles to the VR distributions in the conventional wind profile, it is observed that (a) the over-speed area (VR>1.3) decreases and (b) the shelter area (VR<0.7) increases in the pedestrian-level wind field under the influence of the twisted profiles.

[1)] Graduate Student
[2)] Graduate Student
[3)] Assistant Professor
[4)] Professor

1. INTRODUCTION

Pedestrian level wind environment is crucial for the comfort and safety of pedestrians in metropolitan areas. For example, on one hand, unpleasant high wind speeds frequently result in pedestrian discomforts and extreme high wind speeds around building corners may pose dangers for outdoor city residents. On the other hand, air pollutants cannot be removed from street canyons if the wind speed is too low to penetrate between buildings. Apart from that, pedestrian level wind field plays a fundamental role in determining thermal comforts of urban residents. Given the importance of pedestrian level wind field, a number of studies have been conducted focusing on the features of the pedestrian level wind field in mega-cities. For example, the wind environment in central area of mega-cities was studied by Mochida and Lun (2008). Moreover, Tsang, et al (2012) studied striking features of wind field around tall buildings with different configurations. Understandably, the pedestrian level wind environment continuously attracts attentions from researchers along with the trend of urbanization.

Since the outbreak of Severe Acute Respiratory Syndrome (SARS) in 2003, which has resulted in a considerable number of casualties in Hong Kong, the importance of pedestrian level wind environment began to be recognized by the Hong Kong government. As a result, the Air Ventilation Assessment (AVA) has been suggested for evaluating new constructions proposed in Hong Kong. The AVA provides an assessment to obtain the influence of new development on the existing pedestrian level wind field around the development site. In detail, a scaled model of the proposed construction is tested in a wind tunnel and wind speeds are measured in the wind tunnel test to evaluate the pedestrian wind environment around the proposed construction. Apparently, the accuracy and reliability of AVA wind tunnel test results are remarkably dependent of the reliability of the approaching wind flow employed in the test.

Understandably, the reliability of the approaching wind flow, to a large extent, determines the realistic level of the AVA test results. Therefore, it is worthwhile to improve the simulation of the approaching wind flow. Conventionally, a power-law model described mean wind profile is utilized to specify the vertical variation of mean wind speeds in the approaching flow in most AVA wind tunnel tests. While the power-law model described wind profile matches with the wind environment in the harbor area of Hong Kong, the mean wind profiles in the proximity of hilly terrains considerably deviates from the power-law model. In order to build up a database recording local wind environments in Hong Kong, a series of wind-tunnel topography studies were conducted in the Wind/Wave Tunnel Facility of the Hong Kong University of Science and Technology. Based on the measurements gathered from 13 wind-tunnel topography studies, which simulate the wind environments at various locations in Hong Kong, it has been found that the vertical variation of wind directions is appreciable for the sites near hills. It is anticipated that the vertical variation of mean wind directions, which will be termed as the twisted wind profile hereafter, is induced by the detours of wind flows passing through three-dimensional hills. The vertical variation of mean wind directions observed in the wind-tunnel topography studies clearly indicates that the mean wind profile described by a simple power-law model is inappropriate to specify the approaching wind flow employed in an AVA wind-tunnel test concerning the constructions near hills. In fact, among 256 profiles tested in 18 wind-tunnel topography studies, more than 40% of the measured wind profiles exhibit the twist effect. If the maximum twisted angle is defined as the difference between the mean wind directions measured near the ground and at the top of the measurement height (500m), 40% of the profiles show a maximum twisted angle exceeding 8^o and 20% of the profiles show a maximum twisted angle exceeding 15^o. The largest maximum twisted angle can be as large as 35^o. From the wind-tunnel topography studies, the twist effect has been found mainly to occur under 300m. It is evident that the twist effect has crucial influences for the wind environment around buildings.

Therefore, when conducting AVA wind-tunnel tests, it is important to consider the twist effect in order to obtain the more realistic pedestrian level wind environment. More specifically, the approaching wind flow employed in the AVA wind-tunnel test should be adjusted according to the observed twist effect when appropriate. Consequently, it is important, from the perspective of AVA wind-tunnel tests, to establish some fundamental understandings on the influence of the twisted approaching wind flow on the pedestrian level wind field around buildings with idealized configurations. Such understanding can be resulted from comparing the pedestrian level wind fields around buildings under the influences of conventionally straight wind flow and the twisted flow with specific features.

Professor Flay (1996) introduced the methodology to simulate twisted profiles in the wind-tunnel test. More specifically, he employed a vertical vane system to shape approaching flow to test the performance of yacht’s sails. In addition, his co-workers (Richards et al., 1996) conducted a series of numerical simulations to examine the influence of the twist effect on the dynamics of yacht’s sails. Their results indicated that it is important and worthwhile to include the twist effect in a wind tunnel test where the vertical variation of mean wind direction is appreciable.

Employing wind-tunnel modelling techniques, this paper investigates the influences of the twisted wind flow on the pedestrian level wind environment around an isolated building with different, idealized configurations. Specifically, two twisted wind profiles with the maximum twisted angles of 13^o and 22^o are modulated in the wind tunnel and the pedestrian level wind speeds are measured. Afterwards, the pedestrian level wind field measured by the wind tunnel is compared to the measurements taken in a conventional wind-tunnel test of the same building model. Then, a discussion on the impact of the twisted profiles is presented to contribute to the understandings on the influence of the twist effect on the pedestrian level wind field.

2. WIND TUNNEL TEST

In order to investigate the influence of the twist effect on the pedestrian level wind field, a series of wind-tunnel tests were conducted in the low wind speed section of the CLP Power Wind/Wave Tunnel Facility at Hong Kong University of Science and Technology. The low wind speed section is 4 m in height and 5 m in width. The maximum wind speed is approximately 8 m/s at 1m over ground. The geometric scale was set to 1:200, which means that the wind speed measured at the height of 10mm in the wind tunnel simulates the wind speed at 2m height at the full scale. In an attempt to obtain the wind fields around the isolated building, more than 200 Irwin sensors were installed around the building model. Meanwhile, two vane systems (1.5m high) were built to generate two twisted wind profiles with the maximum twisted angles of 13^o and 22^o at 10mm height. The two twisted profiles are named as TWP13 and TWP22 profiles according to the maximum twisted angle of the profile. At the center of the turntable, five isolated building models were placed to study how the building dimension influences the pedestrian level wind environment around an isolated building.

2.1 Twisted wind flow modelling

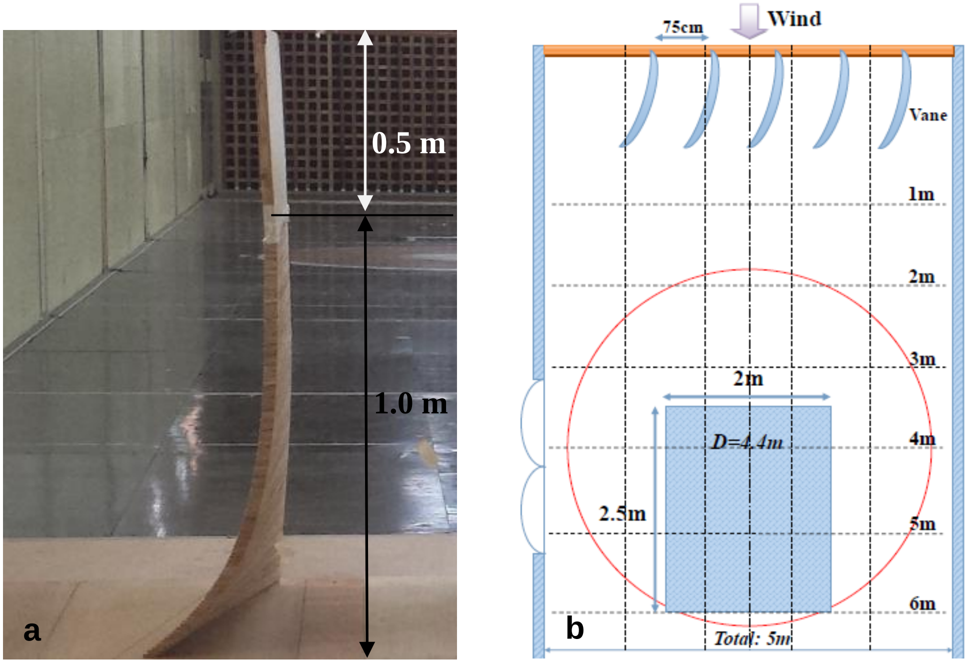

Fig. 1 (a) Vertical Vane System; (b) Measurement area with consistent airflow (shadow area)

In this study, three approaching wind profiles were modulated in the wind tunnel: a conventional wind profile (labeled as CWP) described by the power-law model, and the TWP13 and the TWP22 profiles. For generating the TWP13 and TWP22 profiles, vertical vane systems (Fig. 1 (a)) are installed at 4m upstream of the turntable center instead of the roughness elements. A vane system consists of five vanes and each vane is 1.5m in height. In order to generate the TWP13 profile, the directions of the vanes gradually change from 15^o at the bottom to 0^o at the 1m height. In other words, the vane system makes the wind incident angle of 15^o gradually reduce to 0^o at the 1m height. Within the height range of 1m~1.5m, straight boards are adopted to keep airflow aloft move in the same direction to prevent eddies. The set-ups of the vane system to generate the TWP22 profile follow the configuration articulated above. It is important to note that, even though the maximum wind incident angles of the flow in the immediate downstream of the vane system are 15^o and 30^o corresponding to the TWP13 and TWP22 profiles respectively, the maximum twisted angles measured at the turntable center in the calibration are reduced to 13^o and 22^o due to wind flow depreciation. In the calibration, it has been found that a rectangular area, which is 2m x 2.5m (width x length) with the center located 0.75m downstream the turntable center, shows consistent twisted wind profiles. The shaded rectangular area is shown in Fig. 1 (b). Consequently, all measurements employed in this study were taken within the specific rectangular area. For generating the CWP profile, the regularly arranged roughness elements were installed upstream of the building model to match the normalized mean wind speed of the twisted profiles. The normalized mean wind speed and turbulence intensity profiles, corresponding to the three approaching wind conditions, are shown in Fig.2 (a). The vertical variations of mean wind directions corresponding to the two twisted wind profiles measured at the center of the turntable are shown in Fig. 2 (b).

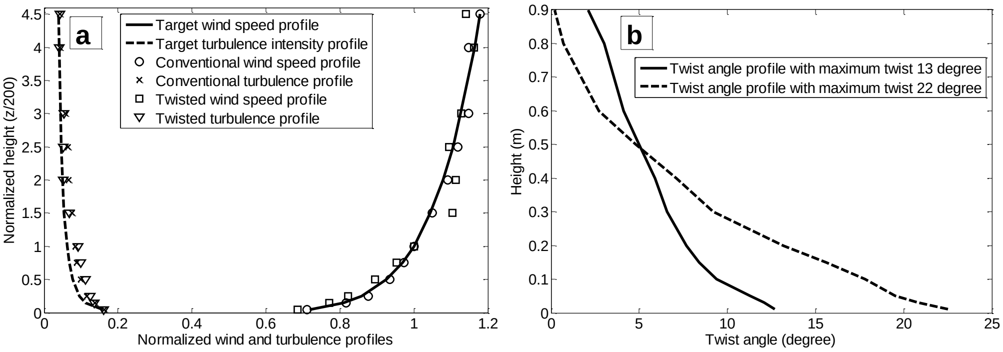

Fig. 2 (a) Normalized mean wind speed and turbulence intensity; (b) Twisted profiles of TWP13 and TWP22 at the centre of turntable.

2.2 The arrangement of Irwin sensor

In this study, the pedestrian level wind field was measured by Irwin sensors. The Irwin sensor is an omni-directional pressure sensors, which is capable of measuring the values of wind speeds. Irwin sensors were developed by Irwin (1981) and improved by Stathopoulos (1994) and Tsang et al. (2012). The Irwin sensors used in this study are similar to those employed by Tsang (2012). The configuration of the sensor is illustrated by Fig. 3 (a). More than 200 Irwin sensors with 10mm long protruded tube were installed around the building model. Considering the geometric scale in the test, 10mm high tube measured the wind speed at 2m high in prototype scale. The wind speed at the top of tube is calculated according to pressure difference between the top and the bottom of the senor according to Eq. 1. The constants α and β are determined from calibration of Irwin sensors. The calibration was conducted through comparing the Irwin sensor measurements to the concurrent measurements taken by a hot-wire anemometer.

All Irwin sensors were arranged around an isolated building as shown in Fig. 3 (b). The front boundary of the area is 375mm upstream from the turntable center, the rear boundary is 1425mm downstream of the turntable center. The lateral boundaries are at a distance of 600mm from the turntable center. It is worth to note that, the grid spacing increases farther downstream of the model taking into account the limited number of available connections and the stability of the pressure scanners; the grid spacing increases from 75mm to 150mm. For all the Irwin sensors, the measurement frequency is 500Hz while the measurement period lasts for 120 seconds.

$$u = \alpha + \beta\sqrt{\Delta p} \tag{1}$$

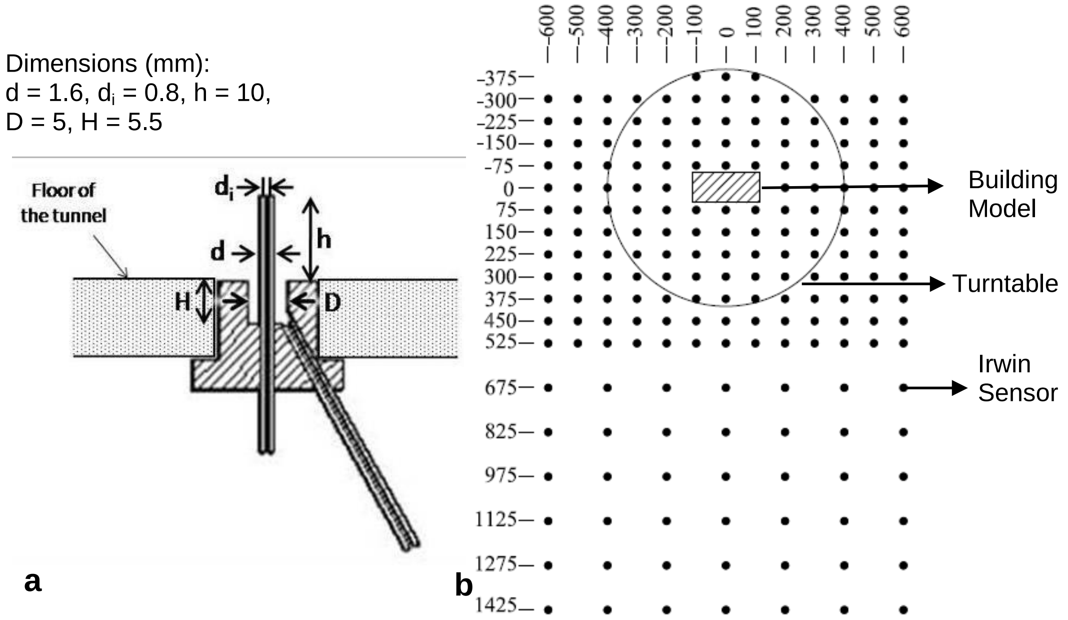

Fig. 3 (a) Dimensions of Irwin sensor, (b) Arrangement of Irwin sensors (dimensions in mm).

2.3 Building model description

Table 1 Building dimensions and aspect ratios of five isolated building models.

Model	Dimensions (H×W×D) (mm)	Aspect ratio (H/W)
M1	600×150×100	4:1
M2	300×150×100	2:1
M3	225×150×100	1.5:1
M4	225×300×100	0.75:1
M5	225×450×100	0.50:1

Building dimensions are certainly a crucial factor significantly influencing the pedestrian level wind field around the building. In order to investigate the impacts of the building height (H) and the building width (W), five building models were manufactured and each of them was tested at the turntable center in sequence. The detailed information on the model dimensions are summarized in Table 1. The building height varies from 600mm (M1) to 225mm (M3) and the building width increases from 150mm (M3) to 450mm (M5). The models M1, M2 and M3 having the same width are used to determine the impacts of building heights and the models M3, M4 and M5 sharing the same height are employed to study the influences of width on pedestrian level wind. The experiment set-ups are illustrated in Fig. 4. It is shown in Fig. 4 that a pitot tube was installed to monitor the reference wind speed.

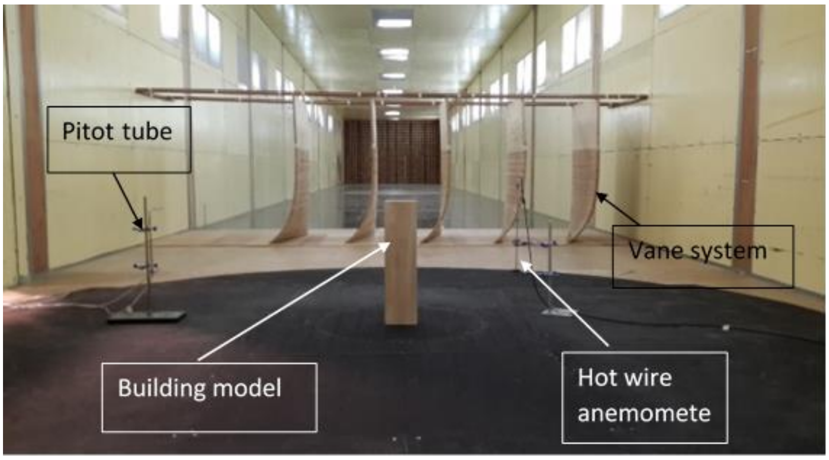

Fig. 4 Building model and vane system set up in low wind speed section of boundary layer wind tunnel

3. RESULTS AND DISCUSSION

In order to systematically show the wind field, a velocity ratio was calculated based on the measurements of pedestrian level wind speeds. The velocity ratio is defined as in Eq. 2. In Eq. 2, $\bar{V}_{(x,10)}$ is the mean wind speed obtained in the test when the building model is placed and $\bar{V}_{a(x,10)}$, which is used as a reference, is the mean wind velocity at the same place but without a building model.

$$\mathrm{VR} = \frac{\bar{V}_{(x,10)}}{\bar{V}_{a(x,10)}} \qquad (2)$$

Besides the employment of velocity ratios, a zoning scheme is utilized to show the variation of the pedestrian level wind speed in a systematical manner. Specifically, five areas were identified according to the location of the building model and the pedestrian level wind strength: upstream far field low wind speed area (UFLWS), upstream near field low wind speed area (UNLWS), downstream near field low wind speed area (DNLWS), downstream far field low wind speed area (DFLWS) and corner stream area (CS).

In an investigation concerning the twist effect, an additional parameter is introduced, i.e. the deviated angle. As shown in Fig. 6, the angle between the along-wind axis and the line connection center of DFLWS and the center of the building was defined as deviated angle, labeled as α. The angle therefore presents the shift of the DFLWS area induced by the twist effect.

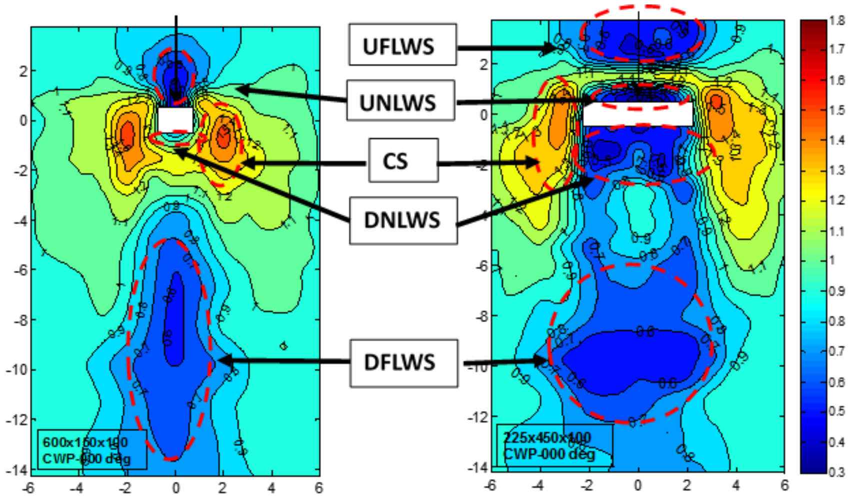

Fig. 5 Main features of wind environment at pedestrian level around single building

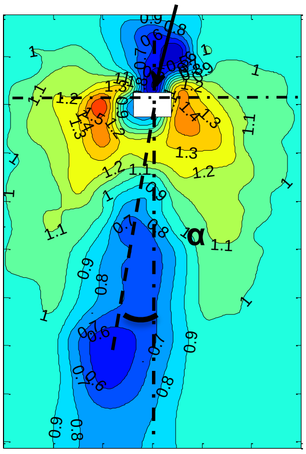

Fig. 6 Definition of deviated angle (α) of UFLWS

3.1 The influence of building heights

The building height obviously has significant influences on the wind field around the buildings, as shown in Fig. 7. In detail, the location of the DFLWS area shifts from the centerline of the building to approximately align with the direction of the approaching wind direction induced by the twisted wind. By comparing the contours shown in Fig.7, it has been found that the deviated angle α reaches the maximum value under the influence of the TWP22 profile. It is worth to note that the DFLWS area shifts from the centerline of the building as the maximum twisted angle increases. In addition, when the building height decreases, the DFLWS area moves towards the building. The feature is more obvious under the influence of the twisted wind. Moreover, it has been found that the size of DFLWS area increases in the twisted wind flow. Such an observation implies that the blocking effect is more prominent when the twist effect is exhibited in the approaching wind flow due to its oblique wind attack angle.

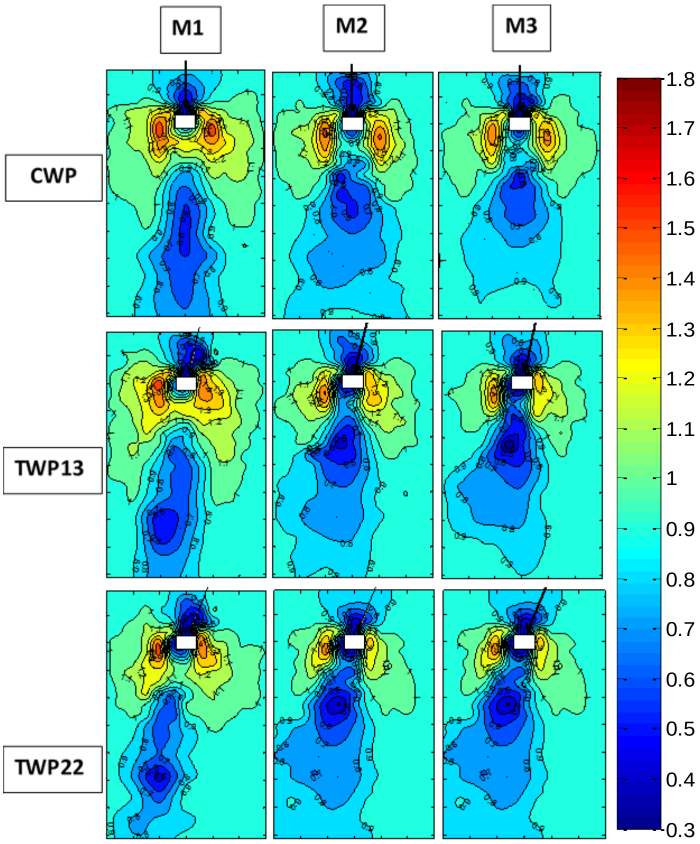

Fig. 7 Contour maps of wind speed ratio around 3 single buildings with different heights (M1: 600×150×100; M2: 300×150×100; M3: 225×150×100, unit in mm)

There is another feature observed from Fig. 7. Specifically, the areas CS on the two sides of the building are asymmetric and under the influence of the twist. In the case of the TWP13 and TWP22 profiles, the velocity ratio in the left corner of the building is found larger than the value in the right corner stream.

In summary, the DFLWS area in the twisted wind flow moves towards the building when the building is shorter. In particular, the deviated angle of the DFLWS area is found increase in the twisted wind flow and the asymmetric CS areas are found more obvious under the influence of the twisted wind profiles.

3.2 The influence of building widths

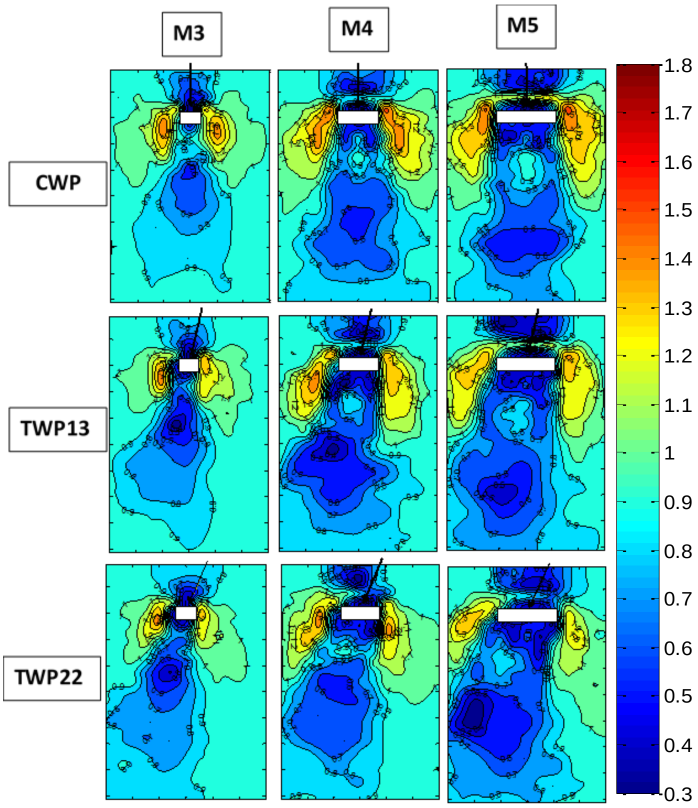

Fig. 8 Contour maps of wind speed ratio around 3 single buildings with different widths (M3: 225×150×100; M4: 225×300×100; M5: 225×450×100, unit in mm)

Table 2 Deviated angles for different buildings models under the three wind profiles

Model	Deviated angle (^{o})		
	CWP	TWP13	TWP22
M1	0º	9º	15º
M2	0º	9º	17º
M3	0º	9º	16º
M4	0º	10º	23º
M5	0º	11º	28º

As presented in Fig. 8, the DNLWS area and the DFLWS area increase with the building width. In addition, the DFLWS area moves further downstream when the building width increases. Through comparing to the contours in Figs. 7 and 8, the UFLWS area appears around the models M4 and M5. It is reasonable to postulate that the downwash on the windward side weakens with the increasing width of the building. As regards the value of α, it increases with the increasing of building width and the maximum twisted angle, as shown in Table 2. The deviated angle, on the contrary, is constant when the building height increases and building width maintains 150mm. In addition to the influence on the low wind speed area, the maximum wind velocity ratio in the CS area reduces with the increase of building width.

3.3 The influence of twisted wind

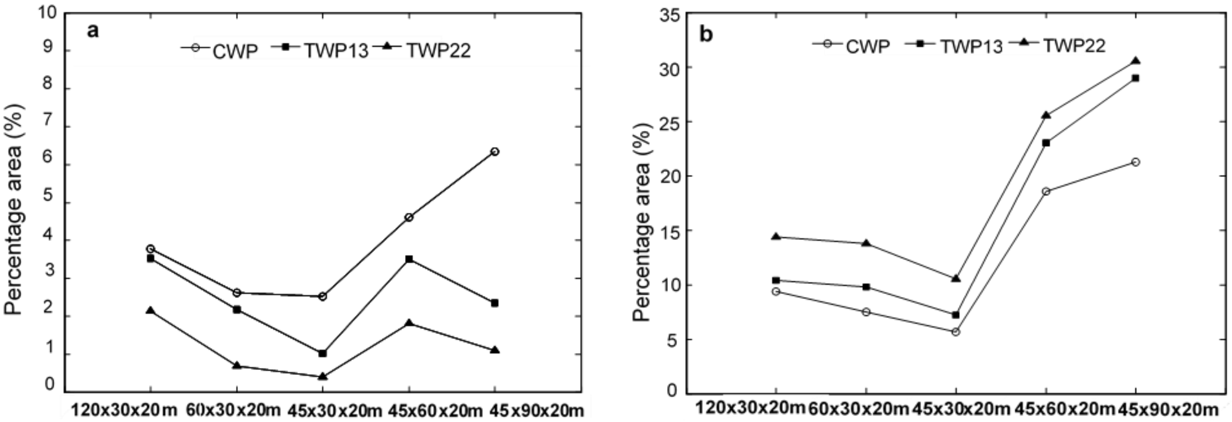

Fig. 9 Percentage area of (a) Over-speed (VR>1.3), (b) Sheltered (VR<0.7)

Besides the influence on the deviated angle and the shift of CS area described above, the twisted wind has considerable influences on the wind speed distribution at the pedestrian level. In order to investigate the variations of the wind speed distributions in the conventional straight flow and the twisted flows, two specific areas, namely the over-speed and sheltered areas, are identified from the VR contours. The over-speed area is defined as the area with VR larger than 1.3 and the sheltered area corresponds to VRs smaller than 0.7. The two specific areas are expressed as a ratio in percentage to the total area covered by the set of Irwin sensors. For the over-speed area, it has little difference under the influences of the CWP and the TWP13 profiles as shown in Fig. 9 (a). When the approaching wind flow is modulated according to the TWP22 profile, there is an appreciable decrease of over-speed area observed from Fig. 9 (a). It is worth to note that, the value of over-speed area percentage appreciably decreases when the building height decreases. In addition, when the building is slender and the maximum twisted angle is small, the increase of the over-speed area percentage is more obvious. As shown in Fig. 9 (b), it is found that the twist effect aggravates the sheltered situation. Furthermore, when the maximum twisted angle increases from 13^o to 22^o, the larger low wind speed area appears in the downstream, which could worsen the air quality due to the undesirable air ventilation situation induced by the interaction between the wider building and the twisted wind flow. Therefore, it can be inferred that the increase of the sheltered area caused by the blocking effect is more significant in the twisted wind flow. This is because the wind attacks both the front and side walls of the building hence the blocking effect is strengthened in the twisted wind flow.

4. CONCLUSIONS

This study has investigated the influence of the twist effect on the pedestrian level wind environment. In detail, five isolated building models with different heights and widths were constructed and tested in the low wind speed section of the CLP Power Wind/Wave Tunnel Facility in Hong Kong University of Science and Technology. As regards the approaching wind flow, three different mean wind profiles, one conventional CWP profile and two twisted wind profile TWP13 and TWP22, were employed. More than 200 Irwin sensors were installed to measure wind speed at 10mm height, which measures wind speeds at 2m height in the prototype scale, to illustrate the wind speed at the pedestrian level. Based on the wind tunnel measurements, it has been found that the shift of the DFLWS area is more apparent in the twisted wind flow. The wider and shorter buildings induce lager deviated angles of the DFLWS area. Moreover, the size of the over-speed area decreases in the twisted wind flow due to the weakened CS area facing to the wind. It has also been found that the twisted wind flow appreciably increases the size of low wind speed areas (sheltered areas). The width of the building also aggravates the sheltered effect, implying bad air ventilations and inefficient air pollutants dispersions. The investigation clearly indicates that the reliability of the approaching wind flow simulated in a wind tunnel test is critical for accurately simulating the pedestrian level wind environment for AVA studies.

REFERENCES

Flay, R.G. (1996), “A twisted flow wind tunnel for testing yacht sails”, *Journal of Wind Engineering and Industrial Aerodynamics*, **63**, 171-182.

Hedges, K.L., Richards, P.J. and Mallinson, G.D. (1996), “Computer modelling of downwind sails”, *Journal of Wind Engineering and Industrial Aerodynamics*, **63**, 95-110.

Irwin, P.A. (1981), “A simple omnidirectional probe for the measurement of pedestrian level winds”, *Journal of Wind Engineering and Industrial Aerodynamics*, **7**, 219-239.

Mochida, A. and Lun, I.Y.F. (2008), “Prediction of wind environment and thermal comfort at pedestrian level in urban area”, *Journal of Wind Engineering and Industrial Aerodynamics*, **96**, 1498-1527.

Tsang, C.W., Kwok, K.C.S. and Hitchcock, P.A. (2012), “Wind tunnel study of pedestrian level wind environment around tall buildings: Effects of building dimensions, separation and podium”, *Building and Environment*, **49**,167-181.

Wu, H. and Stathopoulos, T. (1994), “Further experiments on Irwin’s surface wind sensor”, *Journal of Wind Engineering & Industrial Aerodynamics*, **53**, 441-452.