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Improving pedestrian level low wind velocity environment in high-density cities: A general framework and case study

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ARTICLE INFO

Keywords:
Pedestrian level wind environment
General design framework
Evaluation criterion
Improvement measures
High-density cities

ABSTRACT

An acceptable pedestrian level wind environment is essential to maintain an enjoyable outdoor space for city residents. Low wind velocity environment can lead to uncomfortable outdoor thermal experience in hot and humid summer, and it is unable to remove the pollutants out of city canyons. However, the average wind velocity at pedestrian level is significantly lowered by closely spaced tall buildings in modern megacities. To improve the low wind velocity environment at pedestrian level in high-density cities, a general framework and detailed guidelines are needed. This study is the first time to develop such a framework, and provide detailed guidelines for improving pedestrian level low wind velocity environment in high-density cities. Additionally, a detailed review and summarisation of evaluation criteria and improvement measures are presented in this paper, which provide additional options for urban planners. To investigate the performance of the framework, the Hong Kong Polytechnic University campus was utilised as a case study. Results showed that pedestrian level wind comfort was greatly improved with the developed framework. The outcomes of this study can assist city planners to improve the low wind velocity environment, and can help policy makers to establish sustainable urban planning policies.

1. Introduction

Outdoor spaces are considered vital constituents of urban environments because they can host entertainment activities that are fundamental to the character of a city and the quality of life of city residents (Chen & Ng, 2012). In particular, outdoor human comfort is extremely important in city planning because it can not only improve the physical and mental health of city residents, but also can help reduce power consumption in residential buildings (Amineldar, Heidari, & Khalili, 2017; Chatzidimitriou & Yannas, 2016; Eltabawi, Hamza, & Dudek, 2016; Kong et al., 2017; Li, Huang, Wu, & Xu, 2018). Actually, an enjoyable outdoor thermal comfort can encourage city residents to spend more time in outdoor spaces (Chen & Ng, 2012; Du, Mak, Huang, & Niu, 2017). However, congested airflow at the pedestrian level has become a major concern in the high-density cities because it is the driving force for the transfer of pollutant, heat, and water vapour (Ai & Mak, 2015; Chatzidimitriou & Yannas, 2017; Ignatius, Wong, & Jusuf, 2015). This problem is more serious in densely built cities at low or mid latitudes, such as Hong Kong and Singapore, which suffer from urban heat island and global warming (Du, Mak, Kwok et al., 2017; Kong et al., 2017; Ng, 2009; O’Malley, Piroozfar, Farr, & Pompeoni, 2015; Yang, Wong, & Jusuf, 2013). Therefore, improving pedestrian level wind environment in high-density cities has become a pressing issue for the establishment of comfortable, healthy, and sustainable cities.

A strong relationship between low wind velocity environments at pedestrian level and unfavourable outdoor living environments has been widely identified in high-density cities (Ignatius et al., 2015). For sub-tropical and densely built cities, such as Hong Kong, the wind speed and radiant temperature are the most influencing factors of pedestrian thermal comfort in hot and humid summers (Niu et al., 2015). In particular, Cheng, Ng, Chan, and Givoni (2012) reported that even in shaded environments, the thermal sensation of respondents was not neutral when wind velocity was below 0.9 m/s during the hot and humid summer of Hong Kong. The cooling effect of wind flow can contribute to the reduction of heat stress in urban cities (Memon, Leung, & Liu, 2010; Priyadarsini, Hien, & Wai David, 2008; Yang & Li, 2011). It was identified that a wind speed of 1 m/s to 1.5 m/s could lower the air temperature by nearly 2 °C (Erell, Pearlmutter, & Williamson, 2012). Thus, low wind velocity environment has a negative effect on outdoor thermal comfort, particularly in hot and humid summers. In addition, the dispersion and dilution of airborne pollutants in the urban environment depend strongly on wind flow because it can help remove pollutants to external surroundings (Ai & Mak, 2014a,b, 2016; Hang & Li, 2011; Kim & Baik, 2004; N’riain, Fisher, Martin, &
Littler, 1998). The outbreak of severe acute respiratory syndrome (SARS) in Hong Kong urged the officials and city residents to consider the pollutant dispersion in their living environment (Li, Duan, Yu, & Wong, 2005). By analysing the results from field measurements, Jones, Fisher, Gonzalez-Flesca, and Sokhi (2000) indicated that traffic pollutants could not be properly dispersed or diluted with weak wind conditions in urban areas. Moreover, low wind velocity environments in the street canyons could not form the coupling process to remove the pollutants from the street canyons to the upper atmosphere (Jones et al., 2000; Vignati, Berkowicz, & Hertel, 1996).

There have been substantial investigations into the improvement of pedestrian level wind environment in the past few decades (Blocken, Stathopoulos, & van Beeck, 2016; Du, Mak, Huang et al., 2017, 2017c; Hang, Sandberg, & Li, 2009; Hang, Li, Sandberg, Buccolieri, & Di Sabatino, 2012; Kubota, Miura, Tominaga, & Mochida, 2008; Liu, Niu, & Xia, 2016; Mirzaei & Haghighat, 2010). Tsang, Kwok, and Hitchcock, (2012) conducted wind tunnel tests to investigate the influence of building dimensions, separations, and podiums on pedestrian level wind environment. Their results indicated that wide buildings with podiums should be discouraged in building designs in high-rise cities, for resulting in large areas of low wind velocity environment around buildings. In the study of Kubota et al. (2008), the relationship between the gross building coverage ratio and the wind environment at pedestrian level from actual Japanese city was quantitatively studied using wind tunnel tests. The results showed that a small gross coverage ratio included the target area, surrounding area, local wind climate, building information, and geomorphological information. It is well known that urban wind flow is very complex and is closely related to the urban morphology, especially in high-density cities. Thus, for scaled models, accurate reproduction of the buildings and geomorphological features of the target area are very important. These

![Design framework for improving pedestrian level low wind velocity environment in high-density city.](Fig. 1)

### 2. Design framework and guidelines

This section describes the design framework and guidelines in detail. Note that the present study only concerns the improvement of low wind velocity environments in high-density cities. However, the general framework developed in this study can also be used to mitigate the nuisance caused by strong wind conditions. In doing so, the improvement measures and evaluation criteria need to be re-determined. A flow chart of the design framework for improving the pedestrian level low wind velocity environment in a high-density city is shown in Fig. 1. Meanwhile, the basic parameters for the design framework are summarized in Fig. 2. Based on Figs. 1 and 2, the detailed guidelines for the improvement of pedestrian level low wind velocity environment are presented as follows:

- **Step 1:** basic information on the target area should be collected before evaluating the wind environment at pedestrian level. This includes the target area, surrounding area, local wind climate, building information, and geomorphological information. It is well known that urban wind flow is very complex and is closely related to the urban morphology, especially in high-density cities. Thus, for scaled models, accurate reproduction of the buildings and geomorphological features of the target area are very important. These
geometric data can be obtained from GIS or government departments. Moreover, the target area should include surrounding buildings and infrastructure, which have a significant impact on the pedestrian level wind environment in the target area. Furthermore, the local wind climate should be acquired from nearby weather stations.

- Step 2: based on the obtained basic information, the wind environment at pedestrian level can be obtained by field measurements (Jones et al., 2000; Niu et al., 2015), wind tunnel tests (Du, Mak, Huang et al., 2017; Kubota et al., 2008; Tsang et al., 2012) or computational fluid dynamics (CFD) simulations (Blocken, Janssen, & van Hooff, 2012, 2016; Du, Mak, Liu et al., 2017; Du, Mak, & Ai, 2018; Tominaga, Mochida, Murakami, & Sawaki, 2008). The field measurements should be conducted for a long time due to the uncertainty and unsteadiness of meteorological conditions (Schatzmann & Leith, 2011; Schatzmann, Rafailidis, & Pavageau, 1997). Moreover, the building models in the wind tunnel tests or CFD simulations should be replicated as close to the real buildings as possible. In addition, the prediction process should rigorously follow the practice guidelines and regulations, such as the AWES and ASCE quality assurance for wind tunnel (ASCE, 1999; AWES, 2001) and COST and AIJ guidelines for CFD simulation (Franke, 2007; Tominaga, Mochida, Yoshi et al., 2008).

- Step 3: the low wind velocity area that needs to be improved can be determined by combining the prediction results obtained in Step 2 and the evaluation criteria. The main features of the evaluation criteria and parameters for improving low wind velocity environments are summarized in Section 3.

- Step 4: the low wind velocity environment can be improved by adopting improvement measures such as using the lift-up design to create a void space underneath the building (Du, Mak, Liu et al., 2017; Niu et al., 2015) or adopting openings in building design to guide wind flow through buildings (Fan, Chau, Chan, & Jia, 2017; Yuan & Ng, 2012). The main findings of previous studies on improving weak wind environment by adopting innovative building designs are detailed reviewed in Section 4.

- Step 5: the pedestrian level wind environment should be re-evaluated after adopting improvement measures. If the improved wind environment meets the requirements of the evaluation criteria, the wind environment in the target area is then viewed as an acceptable wind environment. Otherwise, new improvement measures should be adopted in the target area as illustrated in Fig. 1.

3. Evaluation criteria

Similar to the fact that strong wind conditions can be evaluated by using the existing wind comfort criteria (Hunt, Poulton, & Mumford, 1976; Isyumov & Davenport, 1975; Lawson, 1978; Melbourne, 1978; Willemsen & Wisse, 2007), the low wind velocity environment should be assessed by suitable evaluation criteria. The wind comfort criteria aimed at assessing low wind velocity environments in high-rise cities have been established in past years. This section presents a detailed review and summarisation of the evaluation criteria for low wind velocity environments, as well as the evaluation parameters for outdoor wind environments.

3.1. AVA scheme

In order to enhance pedestrian level wind ventilation, the Hong Kong government has stipulated elaborate technical guidelines and protocols, titled “Feasibility study for establishment of air ventilation assessment (AVA) system” (Ng, 2009). This AVA scheme was established specifically for low wind conditions in the high-density urban area. The main purpose of the AVA scheme is to improve wind flow movement at pedestrian level and to assess the influence of newly built developments on the neighbouring wind environment. The principle of the AVA scheme is “the more, the better”; and thus only a low wind threshold value was established in this scheme (Ng, 2009). This means that the pedestrian level wind environment is acceptable when the wind velocity is over 1.5 m/s for 50% of the time.

3.2. New wind comfort criteria

It can be seen that the AVA scheme aiming for enhancing pedestrian level wind environment has no specific regulations on wind comfort. Unlike the wind comfort criteria adopted from overseas, which mainly focuses on strong wind conditions (Hunt et al., 1976; Isyumov & Davenport, 1975; Lawson, 1978; Melbourne, 1978; Willemsen & Wisse, 2007), the new wind comfort criteria proposed in our earlier study are intended specifically for low wind velocity environments (Du, Mak, Kwok et al., 2017). Additionally, the new wind comfort criteria are established seasonally in consideration of the subtropical weather conditions in Hong Kong. A low wind threshold parameter from AVA scheme was adopted for hot season criteria. Moreover, the parameters in the new wind comfort criteria were chosen by thoroughly reviewing the existing wind comfort criteria to adapt to low wind conditions. Similar to the indicators in the AVA, the mean wind velocity ratio (MVR) and overall mean wind velocity ratio (OMVR) were utilised as indicators in the new wind comfort criteria. These two indicators are defined as follows:

\[ MVR_i = \frac{MV_i}{MV'_i} \]  
\[ OMVR = \sum_{i=1}^{n} R_i \times MVR_i \]  

here, \( i \) is the approaching wind direction; \( MV_i \) is the mean wind velocity at any area of pedestrian level when the approaching wind direction is \( i \); \( MV'_i \) is the mean wind velocity at a reference height (200 m in the prototype) when the approaching wind comes from \( i \) direction; and \( R_i \) is the occurrence probability of approaching wind coming from \( i \) direction.

As mentioned earlier, the OMVR is used directly instead of using actual wind velocity because of its convenience for scaled models, namely CFD simulation which can provide sufficient spatial data or wind tunnel measurement when sufficient measurement points are
used. Note that the application of wind comfort assessment can also be achieved by on-site measurement on the condition that the monitored points are sufficient enough and the wind data has been monitored for a long time, i.e. several months or years. Details of the new wind comfort criteria are listed in Table 1.

### 3.3. **Assessment parameter**

Apart from the above two criteria that focus on low wind environment at pedestrian level, different parameters for evaluating the outdoor wind environment in urban areas have also been proposed and utilized in current researches. Some of them were adopted from indoor ventilation research. Detailed descriptions of the commonly used assessment parameters and their corresponding studies are summarized in Table 2.

### 4. **Overview of improvement measures**

In view of the congested airflow in high-rise cities, many innovative building designs (passive and active) have been intensively investigated in the past few years. Since the geometric characteristics of buildings can modify airflow patterns at pedestrian level, specific building designs should be deployed to improve pedestrian level wind environment. This section provides a detailed review of the improvement measures in current studies, which also provides additional options for city planners to improve the low wind velocity environment at pedestrian level.

#### 4.1. **Lift-up design**

The lift-up design, in which the main building structure is elevated off the ground by pillars or a combination of columns and shear walls, is a potential solution for improving the low wind velocity environment at pedestrian level. A schematic diagram and a photo of the lift-up design in a university campus are shown in Fig. 3. The void place underneath the elevated building is known as the lift-up area. The main purpose of the lift-up area is to minimize the wind flow obstruction at pedestrian level and to function as a corridor for the wind flow. Thus, the wind environment at pedestrian level is improved significantly. Moreover, the lift-up area can be utilised as a passageway for pedestrians, recreational zone, and parking zone.

Several studies have investigated the effect of the lift-up design on improving low wind velocity environment in high-density cities. They reported a clear correlation between wind speed enhancement and the implementation of lift-up design, and suggested that it was necessary to adopt lift-up design in urban planning and architectural design. A field

### Table 1

New wind comfort criteria for Hong Kong (Du, Mak, Kwok et al., 2017).

| Category       | Threshold velocity  | Exceedance probability | Activity description      | Category       | Threshold velocity  | Exceedance probability | Activity description      |
|----------------|----------------------|-------------------------|---------------------------|----------------|----------------------|-------------------------|---------------------------|
| Unfavorable    | OMVR < 1.5/MVₚ       | 50%                     | N/A                       | Acceptable     | OMVR < 1.8/MVₚ       | 2%                      | Sitting Long             |
| Acceptable     | OMVR ≥ 1.5/MVₚ       | 2%                      | Sitting Long              | Tolerable      | OMVR < 7.6/MVₚ       | 2%                      | Strolling                |
| Tolerable      | OMVR > 7.6/MVₚ       | 2%                      | Not suitable for activities| Intolerable    | OMVR > 7.6/MVₚ       | 2%                      | Not suitable for activities|
| Danger         | OMVR > 15/MVₚ        | 0.05%                   | Dangerous                 |                |                      |                         |                           |

### Table 2

Assessment parameters for the outdoor wind environment.

| Parameters           | Description                                                                 | Model configurations                                                                 | Ref.           |
|----------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------------------|----------------|
| Flow rate (Q)        | Calculated as the ratio between the flow entering the target area and the   | Generic/3D/Circular block with 2 or 4 sectors                                         | (Skote, Sandberg, Westerberg, 2005) |
| Purging Flow Rate (FFR) | The net flow rate needed to remove pollutants. A small FFR value means that | Generic/3D/Parallel buildings                                                        | (Blocken, Carmeliet, & Stathopolous, 2007) |
|                      | the domain has limited airflow movement.                                      | Generic/3D/Round shaped, square, rectangular city model                               | (Hang, Li, Sandberg, & Claesson, 2010, 2009a) |
|                      |                                                                           | Generic/3D/Courtyard                                                                   | (Moonen, Doer, & Carmeliet, 2011)       |
|                      |                                                                           | Generic/3D/Two-building model and building arrays                                     | (Bady, Kato, & Huang, 2008)            |
|                      |                                                                           | Generic/3D/High-rise square arrays                                                    | (Hang, Li, Sandberg et al., 2012)      |
|                      |                                                                           | Generic/3D/Aligned arrays, semi-open street roof                                     | (Hang et al., 2013)                    |
|                      |                                                                           | Generic/3D/Aligned and staggered building arrays                                     | (Lin, Hang, Li, Luo, & Sandberg, 2014) |
| Air change rate (ACH) | The value of air change in volume per hour for the domain. A small ACH value  | Generic/3D/Street void model                                                         | (Bu, Kato, Ishida, & Huang, 2009)      |
|                      | means that the domain has limited airflow movement.                          | Generic/2D/Street canyon                                                              | (Li, Liu, & Leung, 2005)               |
|                      |                                                                           | Generic/2D/Street canyon                                                              | (Liu et al., 2005)                     |
|                      |                                                                           | Generic/3D/Long street canyon                                                        | (Hang et al., 2010)                    |
|                      |                                                                           | Generic/3D/Aligned arrays of cubes                                                    | (Hang & Li, 2010a,b)                   |
| Local mean age of air (τ) | The time required for a portion of the airflow to get to a specified point   | Generic/3D/Rownd, square, long rectangular city model                               | (Hang et al., 2009a)                   |
|                      | after entering the domain. A small τ value means that the domain is poorly   | Generic/3D/Long street canyon                                                        | (Hang, Li, Buccolieri et al., 2012)    |
|                      | ventilated.                                                                 | Generic/3D/Aligned arrays, semi-open street roof                                    | (Hang et al., 2013)                    |
|                      |                                                                           | Generic/3D/Building array of cubes                                                    | (Buccolieri et al., 2010)              |
measurement study in the HKPolyU campus found that wind speed was amplified by the lift-up design in a local precinct (Niu et al., 2015). Xia, Liu, Niu, and Kwok, (2015) assessed the influence of the lift-up design on the pedestrian level wind environment using wind tunnel measurement, and found that integrating the lift-up design in existing building configurations can enhance the wind speed around buildings. In a study of Du, Mak, Liu et al. (2017), the effects of the lift-up design on pedestrian level wind environment in different building configurations, namely the slab shaped building, the corner shaped building, the semi-open shaped building and the close shaped buildings, were quantitatively evaluated using CFD simulation. The results showed that the lift-up design could effectively improve the low wind velocity environment and its enhancement highly relied on the approaching wind direction. Tse et al. (2017) found that the lift-up core dimensions govern the pedestrian level wind speed around an isolated building using wind tunnel measurement, and suggested that proper core dimensions should be selected before implementing the lift-up design in architectural design. Similarly, Du, Mak, and Li (2018) proposed a multi-variable optimization method to determine the appropriate lift-up dimensions for an optimum wind environment at pedestrian level using CFD simulation. Liu et al. (2016, 2017) studied the pedestrian level wind environment around isolated buildings with and without the lift-up design using CFD simulation, and found that the lift-up design could improve the wind speed around isolated buildings, but the effects were only limited to the neighbouring area. The above mentioned studies confirm that the lift-up design is a promising solution for low wind velocity environments in densely built urban areas, especially at pedestrian level.

4.3. Building opening

The building opening design is a solution that enhances wind speed by increasing the permeability of buildings. Fig. 5 shows a schematic diagram of a building opening and a photo of the opening design utilised in a real building. Based on the CFD simulation results, Yuan and Ng (2012) concluded that building openings could enhance wind speed in compact urban canyons without losing land use efficiency. Their study also suggested that a higher pedestrian level wind velocity could be achieved when the opening was closer to the ground level and when the size of the opening was larger. In a study conducted by Fan et al. (2017), different types of building openings inside canyons were investigated using CFD simulation. The study concluded that building openings could effectively improve the low wind velocity environment, and considering the values in the development floor area, an opening value of 10% was enough to improve the low wind velocity environment. Moreover, the CFD simulation studies by Hang and Li (2010a), Hang and Li (2011) indicated that the airflow ventilation rate could be improved significantly when buildings in a compact array were open-based (have openings underneath the building). Thus, the building

![Diagram](image)

Fig. 3. (a) Schematic diagram of the lift-up design. (b) Photo of the lift-up design in a university campus.

![Diagram](image)

Fig. 4. (a) Schematic diagram of the arcade design; (b) Photo of the arcade (front view); (c) Photo of the arcade design (side view).
opening design presents prominent advantage in improving the low wind velocity environments in compact high-rise cities.

4.4. Building disposition

Aside from the specific architectural designs that can be integrated into building configurations, building disposition has been proven to improve pedestrian level wind environment around compact and tall buildings. To improve the low wind velocity environments, strategies including low building area density (2011, Buccolieri, Sandberg, & Di Sabatino, 2010; Hang & Li, 2010a), low building aspect ratio (Hang, Li, Buccolieri, Sandberg, & Di Sabatino, 2012; Ho, Liu, & Wong, 2015; Liu, Leung, & Barth, 2005), non-uniform building height (Gu, Zhang, Cheng, & Lee, 2011; Hang & Li, 2010a; Hang, Li, Sandberg et al., 2012; Nelson, Pardyjak, Klevicki, Pol, & Brown, 2007), street orientation (Hang, Sandberg, & Li, 2009, b, Ramponi, Blocken, de Coo, & Janssen, 2015) and aligned arrays (Coceal, Thomas, Castro, & Belcher, 2006; Hanna, Tehrani, Carissimo, Macdonald, & Lohner, 2002) have been used in precinct planning. The key findings of the building arrangements and their contribution towards improving low wind velocity environments are summarized in Table 3.

4.5. Active ventilation system

It is noteworthy that the above mentioned measures are passive strategies to improve low wind velocity environments in high-density cities. In studies conducted by Mirzaei and Haghighat (2010), Mirzaei and Haghighat (2011), an active pedestrian level ventilation system was proposed. The basic idea of this system was that it induced airflows from the roof of the building through ventilation ducts to pedestrian level in the street canyon. The performance of the ventilation system under different atmospheric conditions was numerically studied using CFD simulations of stable, neutral, and unstable conditions. Additionally, different ventilation strategies had been proposed for the ventilation system. Their investigation results indicated the application feasibility of the pedestrian level ventilation system. More detailed information on this active pedestrian ventilation system can be found in the studies of Mirzaei and Haghighat (2010); Mirzaei and Haghighat (2011).

4.6. Comparison of improvement measures

From the above the above literature review, the effectiveness of different improvement measures can be summarized as follows: (i) the building dispersion can improve wind environment in the whole city, and the pedestrian level wind environment can be affected subsequently. However, this improvement measure may lead to low land use efficiency and it is impractical for the existing urban areas. (ii) The arcade design and the lift-up design can enhance wind ventilation at pedestrian level directly without sacrificing any land use, but the result of the arcade design is less effective than the lift-up design. (iii) The position and size of the building opening can affect the effectiveness of the improvement. (iv) The active strategy of the pedestrian level ventilation system is more controllable than the above passive building design, but it requires energy consumption. Thus, the passive strategy should be preferred over active strategy for the sustainability of city development.

5. Case study

5.1. Target area

The HKPolyU campus was selected as the study area in this study. The campus is located in the downtown area of Hong Kong, which is closely surrounded by tall and dense buildings. Despite the meteorological advantage of being adjacent to the Victoria Harbour, the pedestrian level wind environment in the campus is low due to the compact neighbouring buildings. To accurately reproduce the wind environment in the campus, surrounding buildings that were up to 1 km from the campus were also included in the model. The campus building information was obtained from architectural drawings, and the geographical data of surrounding buildings were acquired from government department.

5.2. Prediction method

To obtain the pedestrian level wind environment in the campus, the wind tunnel test approach was utilised in this study. The CLP Power Wind/Wave Tunnel Facility (WWTF) at the Hong Kong University of Science and Technology (HKUST) were used to conduct the wind tunnel tests. The scaled ratio for the campus model with its surroundings was 1:200, and the campus model was reproduced in great detail (see Fig. 6(a)). 16 wind directions were measured during the wind tunnel tests at an interval of 22.5° from 0° (North) to 360°. A reference sensor was located at 1 m high (200 m in full-scale) above the edge of the turn table on the windward side. The approaching wind profiles were acquired by grouping and fitting from previous topographic study, which could represent local wind conditions in real life. The measured and target values of the wind profiles and their corresponding approaching wind directions are presented in Fig. 6(b), where the mean wind velocity at the reference height (200 m in prototype) was around 8 m/s. The measured errors were within 5%, which confirmed the confidence in the measurement data. The similarity requirements were strictly examined during the wind tunnel tests, and the blockage ratio was 4.5% with Reynolds Numbers (Re) over $7 \times 10^6$. These met the requirements of the quality wind tunnel test standards ASCE (1999) and AWES (2001) manuals). The Kanomax velocity sensors were utilised for the measurements of pedestrian level wind environment, and they were
evenly distributed in the campus model. Moreover, the Kanomax velocity sensors were carefully calibrated before the wind tunnel measurements.

5.3. Evaluation criterion

As indicated in Section 3.2, the new wind comfort criteria proposed by Du, Mak, Kwok et al. (2017) were developed specifically for low wind velocity environment. In particular, the parameters in the new wind comfort criteria were chosen explicitly to adapt to the low wind velocity environment in Hong Kong. Moreover, the new wind comfort criteria were established seasonally in consideration of the subtropical weather conditions in Hong Kong. Thus, the proposed new wind comfort criteria are adopted as the evaluation criteria in this case study. A detailed description of the new wind comfort criteria is presented in

Section 3.2. With respect to the fact that the hot and humid summer is the critical season in Hong Kong, only the wind comfort for summer is considered in this study. It should be mentioned that the mean wind velocity at 200 m (reference height) in Hong Kong is 5 m/s in the summer season (Planning Department of the HKSAR, 2018). The wind comfort levels and their corresponding threshold values for the HKPolyU campus are presented in Table 4.

The local wind climate for the HKPolyU campus was acquired by calibrating hourly wind data from 2013 to 2015 from a nearby weather station, namely the King’s Park Meteorological Station of the Hong Kong Observatory. Detailed information on the meteorological station can be found in the website (Observatory, 19 December 2012). The wind rose in summer for HKPolyU campus is presented in Observatory (2018) Fig. 7.

Fig. 6. (a) Photo of the HKPolyU campus model during wind tunnel tests: wind from the north (0°). (b) Approaching wind profile: blue is for Profile A (wind directions: 0°, 45°, 90°, 112.5°, 135°, 180°, 202.5°, 225° and 292.5°) and red is for Profile B (remaining wind directions).
5.4. Preliminary evaluation results

To facilitate the illustration of the developed framework, the lift-up areas in the campus model were firstly blocked during the wind tunnel tests, as shown in Fig. 8. This means that there was no lift-up design in the campus model for this case (preliminary case).

The evaluation results of wind comfort in summer for the preliminary case are presented in Fig. 9. It can be seen that in the central part of the campus, the areas around building Y and the area between core A and core B had higher O\textit{MX}R values than the other parts of the campus. Thus, these areas had acceptable wind comfort. Besides, the majority of the campus had low O\textit{MX}R values, which lead to unfavourable wind comfort. Furthermore, nearly 80% of the spaces in the campus were unfavourable for any pedestrian activity. In general, the wind comfort in the campus was not suitable for pedestrian activities in hot and humid summers.

5.5. Adopting the lift-up design

Taking the sustainability of the city development into consideration, the passive building designs are used in this case study. As concluded in Section 4.6, the arcade design and the lift-up design can both improve the pedestrian level wind environment directly, but the lift-up design is more effective than the arcade design. Thus, the lift-up design is adopted as the improvement measure in this case study. Buildings that adopted the lift-up design are indicated on the campus map by blue dashed lines in Fig. 10.

Fig. 11 presents the wind comfort evaluation results after adopting the lift-up design in the campus. As shown in Fig. 11, the central parts of the campus had higher wind speeds than other parts of the campus, and most of the lift-up area had acceptable wind comfort. For the podium area in the campus, the area of acceptable wind comfort was larger than that in the preliminary case. Overall, less than 60% of the spaces in the campus were unfavourable for pedestrian activities. Compared to the preliminary case, the wind comfort in the campus was greatly improved after adopting the lift-up design. However, large areas in the campus still had unfavourable wind comfort.

5.6. Adopting opening in building

The opening design is also effective in improving pedestrian level

![Fig. 7. Wind roses with frequency distribution of the hourly mean wind velocity at 200 m for the HKPolyU campus in summer (Jun.-Aug.).](image)

![Fig. 8. Photo of lift-up blockage during the wind tunnel tests.](image)

![Fig. 9. Preliminary wind comfort evaluation results for summer.](image)

![Fig. 10. Illustration of buildings adopting the lift-up design on campus.](image)

![Fig. 11. Wind comfort evaluation results after adopting the lift-up design for summer.](image)
wind environment. As summarized in Section 4.6, the location and size of the building opening are important in improving pedestrian level wind environment. Thus, the opening design is adopted in building Y because the building Y is the highest and slab-shaped building in the campus. Since the building Y is on the edge of the campus, the opening design is located in the centre of the building Y. Fig. 12 shows the photo of the opening design in building Y during wind tunnel tests. Note that the dimensions in Fig. 12 are in prototype.

Fig. 12. Photo of the opening design in Y building.

Fig. 13. Wind comfort evaluation results after adopting the lift-up design and the opening design for summer.

wind environment. As summarized in Section 4.6, the location and size of the building opening are important in improving pedestrian level wind environment. Thus, the opening design is adopted in building Y because the building Y is the highest and slab-shaped building in the campus. Since the building Y is on the edge of the campus, the opening design is located in the centre of the building Y. Fig. 12 shows the photo of the opening design in building Y during wind tunnel tests. Note that the dimensions in Fig. 12 are in prototype.

Fig. 13 shows wind comfort evaluation results after adopting the lift-up design and the opening design in the campus model. Compared to Fig. 11, the wind comfort of the areas between building M and building Y had significantly improvement after adopting the opening design in building Y. Besides, more than 50% of the places in the campus had acceptable wind comfort, which suggested satisfactory wind comfort for pedestrian activities. Thus, the wind comfort in the campus for summer was significantly improved after adopting lift-up design and opening design. Considering that the majority areas in the campus had acceptable wind comfort, the wind comfort in the campus could be viewed as acceptable in general.

5.7. Overall mean wind velocity (OMVR)

To quantitatively assess wind comfort by adopting the above mentioned improvement measures, this section presents the results of OMVR in three cases. The results of OMVR in three cases are given in Fig. 14. It can be seen that when the campus had no improvement measures (preliminary case), nearly 80% of OMVR values were below 0.3, which meant that nearly 80% of the areas in the campus had unfavourable wind comfort. After adopting lift-up design in the campus, the values of OMVR had been greatly improved. However, half of the OMVR values were still below 0.3. Nevertheless, by adding opening in Y building, the values of OMVR were further improved and more than half of the OMVR values were over 0.3. This suggested that more than half of the areas in the campus had acceptable wind comfort.

6. Conclusion

To stress the importance of improving low wind velocity environments in high-density cities, the influences of low wind velocity environments on pollutant dispersion, thermal comfort, and wind comfort were presented in this paper. A general design framework was developed, and detailed guidelines on improving the pedestrian level low wind velocity environment in high-density cities were offered. The general design framework was presented in the form of a flowchart, which was systematic and effective. Evaluation criteria that aim to improve the low wind velocity environment were also reviewed in detail, namely the AVA scheme, the new wind comfort criteria for Hong Kong, and city ventilation parameters. Moreover, the strategies used to improve low wind velocity environments were reviewed in detail, including the lift-up design, the arcade design, the building opening, building disposition, and the active pedestrian ventilation system.

A case study of an existing university campus was used to investigate the performance of the proposed design framework. Wind tunnel tests were conducted to obtain the pedestrian level wind environment in the campus model. The choice of the evaluation criteria were chosen based on the review results presented in Section 3, and the new wind comfort criteria were selected. The wind comfort of the campus model was improved by vigorously following the proposed design framework, and the improvement measures were chosen based on the review results presented in Section 4. Specifically, three distinctive cases were examined, namely the campus model without the

Fig. 14. Box plots of OMVR results in three cases.
The low wind velocity environment can be improved by following the proposed design framework, which also corresponds with government policies of enhancing ventilation in high-rise cities. In particular, the evaluation criteria and the improvement measures reviewed in this study can be used in practical developments. For example, the lift-up design could be used to improve the pedestrian level wind environment for an existing urban area. These findings can help urban planners and policy makers improve low wind velocity environments at pedestrian level, and build a sustainable city.

Acknowledgement

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. C5002-14 G).

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