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Towards an integrated method to assess effects of lift-up design on outdoor thermal comfort in Hong Kong

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Abstract

City residents wish to have pleasant experience in outdoor space, which are often impeded by thermally uncomfortable conditions, particularly in hot and humid summer. Lift-up design can provide comfortable microclimate in summer but the effects of lift-up design on thermal comfort in a built-up environment have not been systematically studied. This paper aims to investigate the effects of lift-up design on outdoor thermal comfort comprehensively, as well as the effects on pedestrian level wind environment. The thermal comfort assessments are carried out by using a proposed integrated method, which combines wind tunnel tests and on-site monitoring to calculate Physiologically Equivalent Temperature (PET) values. The Hong Kong Polytechnic University (HKPolyU) campus is selected as study area. The investigation mainly focuses on summer and winter seasons. Four typical days in a year were chosen to carry out on-site monitoring for obtaining environmental parameters. This study demonstrates that the proposed integrated method can be used to predict outdoor thermal comfort. Results also show that lift-up design can effectively improve pedestrian level wind environment and thermal comfort. Moreover, lift-up design can provide a comfortable microclimate in summer while not cause strong cold stress in winter. These findings provide solid evidence bases to city planners and architects of available options for creating pleasant outdoor microclimate in precinct planning.

Keywords: *Lift-up design; Thermal comfort; Integrated method; Wind tunnel test; On-site monitoring*

Introduction

Comfortable outdoor environments can encourage people to go outside and enjoy leisure activities, such as walking, jogging and cycling. Besides, outdoor activities can also help efficiently reduce building energy consumption that constitutes more than 60% of energy needs in Hong Kong in 2016 [1]. However, outdoor thermal comfort is often impeded by uncomfortable conditions, like intense solar radiation, unfavourable wind environment, high temperature and so on [2-8]. Meanwhile, recent studies have demonstrated that the average temperature of Hong Kong shows a rising trend and the unbearable hot and humid period has become remarkably longer than the past century [9]. Moreover, future projections have indicated that the period will continue in the 21st century and extreme high temperature events in Hong Kong will notably increase in the future [10]. Apart from high temperature problem, the stagnant air at pedestrian level also causes thermally uncomfortable environment in the hot and humid summer [11]. Therefore, against the background of global climate change and rapid urbanization, the creation of a thermally comfortable microclimate is very much desired in hot and humid Hong Kong [11-14].

A considerable amount of investigations have been carried out to improve microclimate thermal comfort in urban context. Two common approaches that have been used to create pleasant microclimate in hot and humid areas are wind amplification and shading techniques [11, 13, 15-18]. It has been confirmed in previous studies that the wind velocity made great difference in thermal comfort, especially in hot and humid regions [11]. The Hong Kong SAR government has established the Air Ventilation Assessment (AVA) scheme with the purpose of enhancing wind velocity at pedestrian level [18]. Hang [16] investigated wind conditions in high-rise long street in a city scale, and the results indicated that tall buildings with wide streets can enhance the city ventilation and remove heat stress. As for shading techniques, Gehl [19] studied the effect of shading on the popularity of sensitive bench in public places. Lin [20] indicated that sufficient shading should be guaranteed for providing thermally comfortable environment in Taiwan. Johansson and Emmanuel [21] clearly stated that shading played an important role in outdoor thermal comfort in tropical cities.

Among numerous techniques that can improve thermal comfort in hot and humid regions, lift-up design that "lifted off" the buildings from ground with modern pillars has become more and more popular in hot and humid cities. This can be attributed to its prominent feature of providing local cooling spot in hot and humid summer due to wind amplification and shading effect, which has been indicated in our previous researches [11, 13, 15, 17, 22]. Niu et al. [11] conducted on-site measurement in the lift-up and podium areas of HKPolyU campus. Xia et al. [22] and Tse et al. [17] both carried out wind tunnel tests to study the effects of lift-up design on pedestrian level wind environment. Du et al. [15] performed numerical simulation to investigate the effects of lift-up design in different building shapes on pedestrian level wind environment. Liu and Niu [13] combined numerical results and on-site monitoring parameters to predict thermal comfort around an isolated building with lift-up design. Previous studies have shown that for the isolated buildings, even though the lift-up design can significantly amplify wind velocity at pedestrian level, the amplification effect is limited to neighbouring areas around the buildings [13, 15, 17, 22]. Besides, the lift-up design in the HKPolyU campus can provide local cooling spot in hot and humid summer [11]. However, the aforementioned studies are mostly focused on isolated buildings and the on-site measurements were only conducted for two summer days. Therefore, there is a lack of systematic study to quantitatively evaluate the potential benefits of lift-up design on pedestrian level wind environment and thermal comfort in a complex urban environment for long term (summer and winter seasons, respectively), which is genuinely needed for fully understanding of the effects of lift-up design on pedestrian level wind environment and thermal comfort.

In the past decades, on-site monitoring approach was used as the main method for evaluating outdoor thermal comfort [7, 8, 12, 23-32]. For instance, Ng and Cheng [12] conducted an outdoor thermal comfort study in Hong Kong by using on-site monitoring approach. The results showed that the meteorological parameters, including air temperature, wind speed and solar radiation intensity, were important for outdoor thermal sensation. Ali-Toudert et al. [26] carried out on-site monitoring approach in an urban street canyon in Germany. They found that the street geometry and orientation had a great impact on the heat stress gained by people under hot conditions. Hwang et al. [28] studied the thermal comfort in workplaces and residences in Taiwan using on-site monitoring approach. The findings revealed that the thermal adaption behaviour of people can be affected by the used thermal adaptation method. Nikolopoulou et al. [29, 30] conducted on-site monitoring in UK, and the findings enriched the understanding of microclimatic characteristics in outdoor urban spaces. However, these studies were merely elucidated thermal comfort characteristics of a particular day and cannot be used to represent long-term thermal conditions [20]. In order to acquire local wind statistics at pedestrian level, wind tunnel test has been intensively utilized [33-36]. The data obtained from wind tunnel tests are usually used to either analyse the local wind environment or utilised as benchmark data for further numerical validation [15, 33, 37]. Kubota et al. [35] employed wind tunnel techniques to study the relationship between building density and pedestrian level wind velocity. Tsang et al. [36] investigated the effects of building dimensions, separations and podium on pedestrian level wind environment. To the best knowledge of the authors, there are few studies that combines these two techniques to predict outdoor thermal comfort for a local precinct.

In this paper, the effects of lift-up design on thermal comfort in a complex environment are investigated by using a proposed integrated method which combines wind tunnel test techniques and on-site monitoring approach. Meanwhile, the effects of lift-up design on pedestrian level wind environment are also systematically studied. In addition, PET is adopted in this paper as thermal comfort index, which is typically and frequently used for evaluating outdoor environment [3, 20, 21, 38]. The study of the HKPolyU campus, which is located in the midtown of Hong Kong, is presented in this study to illustrate the proposed method. The wind tunnel tests of the campus model were conducted correspondingly. The environmental parameters of four typical days were obtained by on-site monitoring techniques: one cloudy day in summer, one sunny day in summer, one cloudy in winter and one sunny day in winter.

The rest of this paper is organised as follows: after introduction, the methodology for obtaining parameters is presented in Section 2. Section 3 describes data analysis method for this study. The effects of lift-up design on pedestrian level wind environment are discussed in Section 4.1 and the effects of lift-up design on thermal comfort are presented in Section 4.2. Finally, Section 5 concludes the paper.

2. Methodology

2.1 On-site monitoring

The environmental parameters which were perceived as influencing parameters for thermal comfort were continuously monitored for four typical days: one cloudy day in summer (Jul. 15, 2016), one sunny day in summer (Aug. 22, 2016), one cloudy day in winter (Dec.6, 2016), and one sunny day in winter (Dec. 12, 2016). Meanwhile, data loggings of the environmental parameters were taken continually from 09:00 am to 18:00 pm for the four typical days. Two sites were selected in the campus as monitoring locations, as shown in the photos of Fig.1: Site 1 was on the podium area of the Ho lu Kong and Kow Pui Chun Square (Fig.1(a)) and Site 2 was in the lift-up area underneath the Chow Yei Ching building (Fig.1(b)). As a matter of fact, this lift-up area is often used for outdoor activities, such as dancing, practicing martial arts and formal exhibitions. On the contrary, the open square is seldom used for holding outdoor activities because of the direct subjection to solar radiation, especially in the hot and humid Hong Kong summer.

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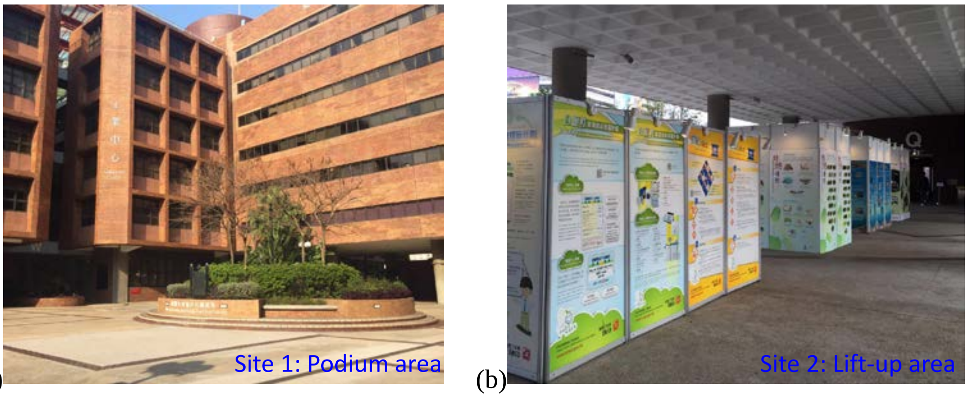


Fig.1. Photos of two selected sites in the HKPolyU campus for on-site monitoring: (a) Site 1: podium area; (b) Site 2: lift-up area.

The mini weather stations were used to measure the environmental parameters in the four sample days at these two selected sites. The monitored environmental parameters were: air temperature (T_a, °C), relative humidity (RH, %), short-wave and long-wave radiation (K_i and K_i (W/m^2), $i = 6$ means six directions perpendicular to each other). It should be mentioned that all the instruments were complied with ISO 7726 standard [39]. The photos of the mini weather station are shown in Fig. 2 and the specifications of measuring instruments are illustrated in Table 1. The data logging was taken 10s intervals during the tests for all the monitored environmental parameters. Besides, all the instruments were carefully pre-tested and calibrated before each on-site monitoring. Noted that only measurement results of net radiometer instrument and T_a & RH sensor, which are specified in Fig.2, are used in this study.

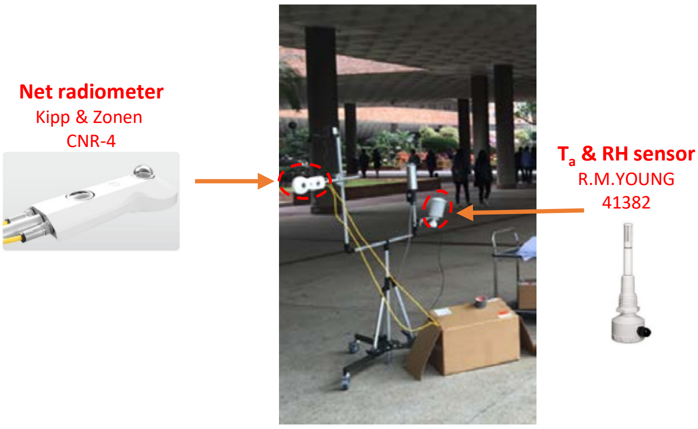


Fig.2. Photo of measuring instruments for mini weather station.

Table 1. Specifications of measuring instruments for mini weather station

Meteorological parameter	Sensor	Measuring Range	Accuracy
Air temperature (T_a)	R.M.YOUNG 41382	-50 ~ 50 (℃)	±0.3℃
Relative humidity (RH)		0 ~ 100 (%)	±1%
Long-wave radiation (L)	Kipp & Zonen CNR-4	-250 ~ 250 (W)	<10%
Short-wave radiation (K)		0 ~ 2000 (W)	<5%

2.2 Wind tunnel tests

The pedestrian level wind velocity was obtained from wind tunnel tests of the HKPolyU campus model. The wind tunnel tests were conducted in the low-speed section of CLP Power Wind/Wave Tunnel Facility (WWTF) at Hong Kong University of Science and Technology (HKUST), which is a closed circuit subsonic boundary layer wind tunnel. This wind tunnel is usually used for civil, structural and environmental engineering applications.

2.2.1 Experiment setup

The mean wind velocity profile of the approaching turbulence wind follows the form of the power law:

$$MV(Z)/MV_{ref} = (Z/Z_{ref})^{\alpha} \quad (1)$$

where, $MV(Z)$ is the mean wind velocity at the height of Z; MV_{ref} is the mean wind velocity at the reference height (200m in prototype); Z_{Ref} is the reference height (200m in prototype, 1m at model scale); α is the power law exponent.

The turbulence intensity profile also follows the form of power law along the height with the negative value of power law exponent. There were 16 wind directions carried out during the tests at an interval of 22.5° from 0° (north) to 360°. After grouping and fitting the wind profile data acquired from previous topographic study, two wind profiles for the campus model were obtained. Profile A was used for the incident wind direction 0°, 45°, 90°, 112.5°, 135°, 180°, 202.5°, 225°, 292.5°, while Profile B was used for the remaining incident wind direction. Besides, all wind tunnel tests were carried out with reference mean wind velocity (MV_{ref}) around 8m/s. Fig. 3 presents the measured and the targeted values of the two wind profiles, and the errors were within 5%, which suggested the accuracy of wind tunnel tests.

(a) (b)

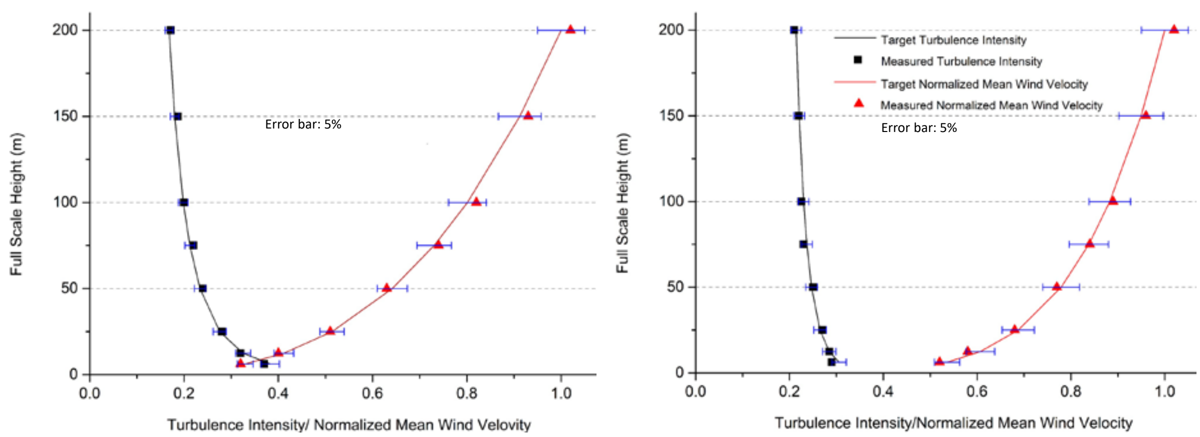
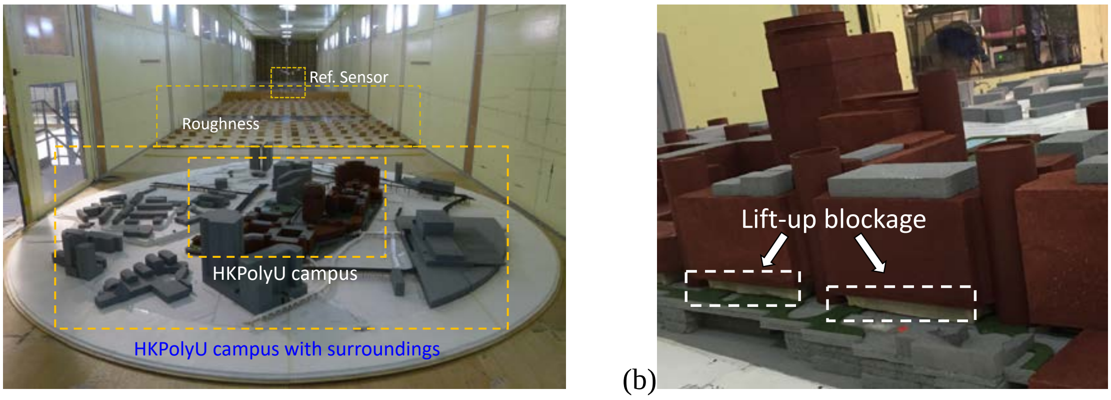


Fig.3 Approaching wind profiles for the wind tunnel tests: (a) Profile A; (b) Profile B.

During the wind tunnel tests, the similarity requirements were carefully checked and boundary conditions were properly selected. The blockage ratio of the tests were 4.5% and the Reynolds Numbers (Re) were over 7.1×10^4, which satisfied the requirements of ASCE and AWES manuals for quality wind tunnel tests [40, 41]. The campus model with its surroundings were scaled and fabricated at 1:200 ratio and the model diameter was 10 kilometres in prototype.

Besides, the model was replicated in great detail, as shown in Fig.4 (a). In order to evaluate the effects of lift-up design on pedestrian level wind environment and thermal comfort in the campus, two distinct cases were carried out during the tests: with and without lift-up design in the campus. The case that without lift-up design in the campus was achieved by blocking lift-up areas in the campus during the tests, as shown in Fig.4 (b).



(a) (b)

Fig.4. (a) Wind tunnel test photo of the HKPolyU campus model: approaching wind direction 0° (wind from north); (b) Photo of lift-up blockage during tests.

Kanomax velocity sensors were used for measuring the wind velocity at pedestrian level during the wind tunnel tests, which have been proven for practical use in wind tunnel studies [17]. Prior to the wind tunnel tests, Kanomax velocity sensors were calibrated firstly against a Cobra Probe which was considered to be accurate enough as a reference sensor. The errors between the Kanomax velocity sensors and the reference sensor are almost within 5%, which manifests the reliability of teste results.

2.2.3 Wind velocity sensor arrangement

The arrangements of Kanomax velocity sensors for the wind tunnel tests are presented in Fig. 5. The letters “A” to “Y” in Fig.5 represent different building cores in the campus, e.g. “A” means A core in the campus. The building between two cores is identified as “building wing”, e.g. the building between G core and H core is “GH wing”. It can be seen that there are some light dashed areas and two different colours of points in the campus model. The light blue dashed areas in Fig.5 means that these buildings have lift-up design underneath the buildings, as shown in Fig.1 (b). The orange points are the measurement points that are located in the lift-up areas. The blue points are the measurement points that are located in podium area, as shown in Fig.1 (a). Besides, the velocity sensors were evenly distributed in the campus during the wind tunnel testes, and Site 1 and Site 2 were the places where on-site monitoring were conducted. Furthermore, in order to interpret the effects of lift-up design on local wind environment, three locations (see Fig.5) were chosen specifically for the following reasons [42]: (i) Position A, which is surrounded by the lift-up designs, has been proven to benefit most from lift-up design in the campus compared to other podium measurement points; (ii) Position B is not adjacent to lift-up design directly and the wind environment is deteriorated by the lift-up design; (iii) Position C is relatively far from lift-up design and the wind environment is insensitive to the lift-up design.

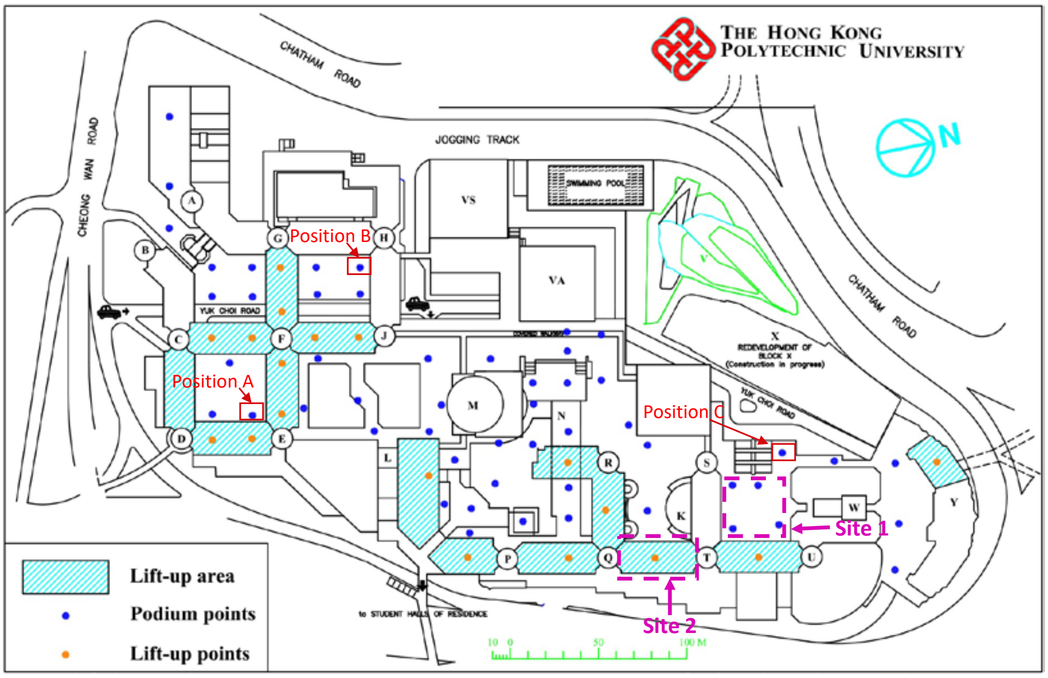


Fig.5. Sensor locations of the campus model.

3. Data analysis method

3.1 Identification of pedestrian level wind parameter

The mean wind velocity ratio(MVR) is adopted here as the pedestrian level wind parameter, which is defined as follows:

$$MVR = MV_p/MV_{ref} \quad (2)$$

where, MV_p is the mean wind velocity at pedestrian level; MV_{ref} denotes the mean wind velocity of approaching flow at 200m in prototype scale (reference height).

As described earlier in the paper, the pedestrian level wind environment was investigated in two distinct cases during the wind tunnel tests: with and without lift-up design. Therefore, the mean wind velocity change ratio (ΔMVR) proposed by our previous study[15] is used here to quantitatively investigate the effects of lift-up design on pedestrian level wind environment. Noted that only the MVR values of podium areas at the campus are used for calculating ΔMVR. The ΔMVR is calculated by the following equation:

$$\Delta MVR = (MVR_{LU} - MVR_{NLU})/MVR_{NLU} \quad (3)$$

here, the subscript "LU" indicates buildings with lift-up design, while the subscript "NLU" means buildings without lift-up design.

To be able to integrate with local wind climate, the overall mean wind velocity ratio ($OMVR$) [43] is adopted in this study, which considers the occurrence probability of each incident wind direction. The definition of $OMVR$ can be seen in the following equation:

$$OMVR = \sum_{i=1}^{n} F_i \times MVR \quad (4)$$

where, F_i is the occurrence probability of approaching wind coming from i direction, which is computed from hourly wind data of King's Park Meteorological Station of the Hong Kong Observatory (HKO) from 1993 to 2015 in this study. n means the number of wind directions considered in this study, which is 16. The wind roses of hourly mean wind velocity with frequency distribution for the HKPolyU campus in summer (Jun.-Aug.) and winter (Dec.-Feb.) are presented in Fig.6 (a) and Fig.6 (b) respectively.

(a) (b)

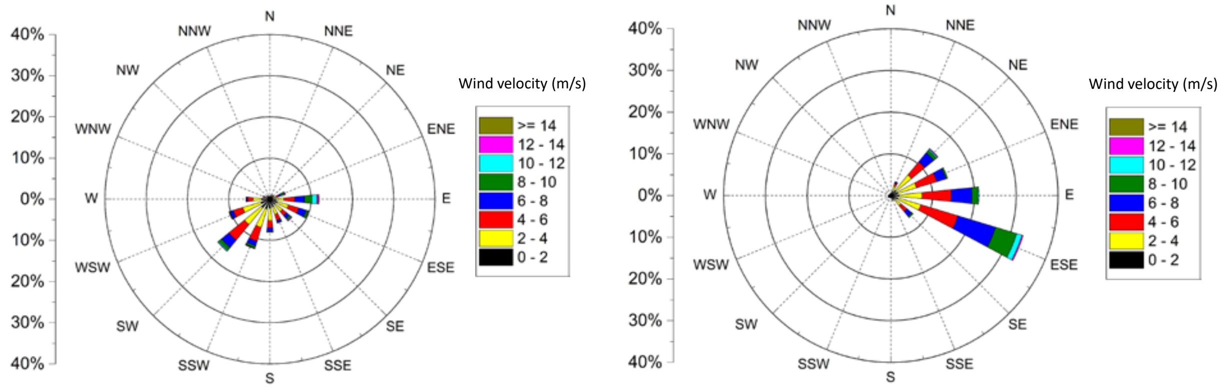


Fig.6. Wind roses with frequency distribution of hourly mean wind velocity at 200m for the HKPolyU campus: (a) Summer (Jun.-Aug.); (b)Winter (Dec.-Feb.).

It should be mentioned that the integrated parameter $OMVR$ is used for assessing thermal comfort in the campus rather than MVR of 16 wind directions. This is because the $OMVR$ is perceived to be more representative for actual environment [43]. However, the values of $OMVR$ cannot be used directly for evaluating thermal comfort. Instead, the values of $OMVR$ should be converted into the in-situ values. According to the recommendation of Willemsen and Wisse [44], the following equation should be established for the quality wind tunnel tests:

$$OMVR_{WT} = OMVR_{IS} \tag{5}$$

where, the subscript "WT" stands for wind tunnel test and the subscript "IS" means in-situ conditions. Therefore, combining Equation (2) and Equation (5) the relationship between the overall mean wind velocity of wind tunnel (OMV_{WT}) and in-situ condition (OMV_{IS}) can be expressed as the following equations:

$$OMV_{p,WT}/OMV_{ref,WT} = OMV_{p,IS}/OMV_{ref,IS} \tag{6}$$

3.2 Identification of thermal comfort parameter

The Physiological equivalent temperature (PET) is adopted in the present study as the thermal comfort index. It is introduced by Höppe [45] for outdoor thermal comfort evaluation and it has advantages in interpreting thermal stress more comprehensible to architecture and urban planners owing to its unit (℃) [46]. PET is based on energy balance of human body and the Munich energy balance model for individuals (MEMI) is therefore used for calculating PET [45, 47].

In order to interpret the subjective thermal perception under different PET values, the PET range should be defined according to pedestrian’s feeling to thermally comfort conditions. There are two sets of range for the subjective thermal perception: one is proposed by Matzarakis et al. for Western/Middle Europe [46]; the other one is modified by Lin and Matzarakis [48] for subtropical Taiwan. Since the weather conditions of Hong Kong are similar to those of Taiwan (hot summer and mild winter), the PET range for Taiwan shown in Table 2 is adopted in this paper.

Table 2. PET range for different grades of thermal perception and physiological stress in Taiwan [48].

PET range for Taiwan (℃)	Thermal perception	Grade of physiological stress
	Very cold	Extreme cold stress
14		
	Cold	Strong cold stress
18		
	Cool	Moderate cold stress
22		
	Slightly cool	Slight cold stress
26		
	Comfortable (Neutral)	No thermal stress
30		
	Slightly warm	Slight heat stress
34		

	Warm	Moderate heat stress
38		
	Hot	Strong heat stress
42		
	Very hot	Extreme heat stress

3.3 Integrated method for PET calculation

The integrated method that is used to obtain PET values of the campus in summer and winter is presented as follows: (i) the measured thermal parameters acquired from the podium area (Site 1) and lift-up area (Site 2) and are used in all the podium areas and lift-up areas in the campus, respectively. (ii) The $OMV_{p,IS}$ values obtained from the wind tunnel tests, are used as the input wind velocity data. It should be noted that the values of $OMV_{p,IS}$ for summer and winter are calculated respectively according to corresponding wind roses presented in Fig.6. (iii) Finally, the measured thermal parameters: air temperature (T_a), relative humidity (RH), mean radiant temperature (T_{mrt}) together with the wind velocity obtained from wind tunnel tests ($OMV_{p,IS}$) are used to calculate PET values in the campus.

The free software, RayMan [49, 50], is utilized here to evaluate the outdoor thermal comfort. Both the environmental parameters and thermal-physiological parameters are required as input parameters for calculating PET. The environmental parameters contain air temperature (T_a, ℃), relative humidity (RH, %), mean radiant temperature (T_{mrt}, ℃) and wind velocity (V_a, m/s); and thermal-physiological parameters include pedestrian physiological information (sex, age, height etc.), clothing insulation (I_{clo}, ℃) and activity type (metabolic rate, W). Noted that in order to accurate represent thermal comfort conditions in summer and winter, the $OMV_{p,IS}$ values calculated from Equation (6) is used as the input parameter of wind velocity (V_a, m/s). In particular, the mean radiant temperature (T_{mrt}) is determined based on six directions of short-wave and long-wave radiation flux densities (K_i and L_i, respectively) [51] and it is calculated by the following methods [52].

$$T_{mrt} = [\frac{\sum_{i=1}^{6} W_i \times (\alpha_k \times K_i + \alpha_L \times L_i)}{\alpha_L \times \sigma}]^{1/4} - 273.15 \quad (7)$$

here, i is six directions perpendicular to each other. W_i denotes direction-dependent weighting factor; for the standing subject, 0.06 for vertical direction while 0.22 for horizontal direction [51]. α_k and α_L are adsorption coefficients for a clothed human body, which is assumed to be 0.7 in the short-wave radiation domain and 0.97 in the long-wave radiation domain [52]. K_i, L_i is short-wave and long-wave radiation flux densities (W/m^2).σ is Stefan–Boltzmann constant, equals to $5.67 \times 10^{-8}\ W/m^2K^4$. In addition, for the calculation of PET, the pedestrian is assumed to be a male of 35 years old, 1.75m height and 75kg weight. The activity of pedestrian is considered to be standing with an internal heat production of 69.8W, which corresponds with the suggested values of ASHRAE Standard 55 [53]. The clothing level is specifically chosen in the context of Hong Kong climate, where winter is mild and temperate while summer is hot and humid. For calculating PET for summer (Jun.-Aug.), the clothing level of 0.3 clo is adopted; and for calculating PET for winter (Dec.-Feb.), the clothing level of 0.7 clo is adopted.

4. Results and discussion

4.1 Effect of lift-up design on pedestrian level wind environment

Using Equation (2), the MVR values at pedestrian level with and without lift-up design in the campus are acquired. Then the differences of MVR values between the campus with and without lift-up design can be calculated from Equation (3). The results of MVR at pedestrian level with and without lift-up design and the values of ΔMVR in 16 approaching wind directions are presented in Fig.7. Obviously, the MVR values at pedestrian level with lift-up design are overall larger than that without lift-up design: the range of MVR is mostly from 0.1 to 0.46 with lift-up design while from 0.1 to 0.41 without lift-up design. Besides, the results of ΔMVR clearly indicate that wind velocity at pedestrian level for 16 wind directions with lift-up design is higher than that without lift-up design since most ΔMVR values are above 0. Moreover, a number of ΔMVR values exceed 100%, suggesting strong wind enhancement at pedestrian level by lift-up design in the campus.

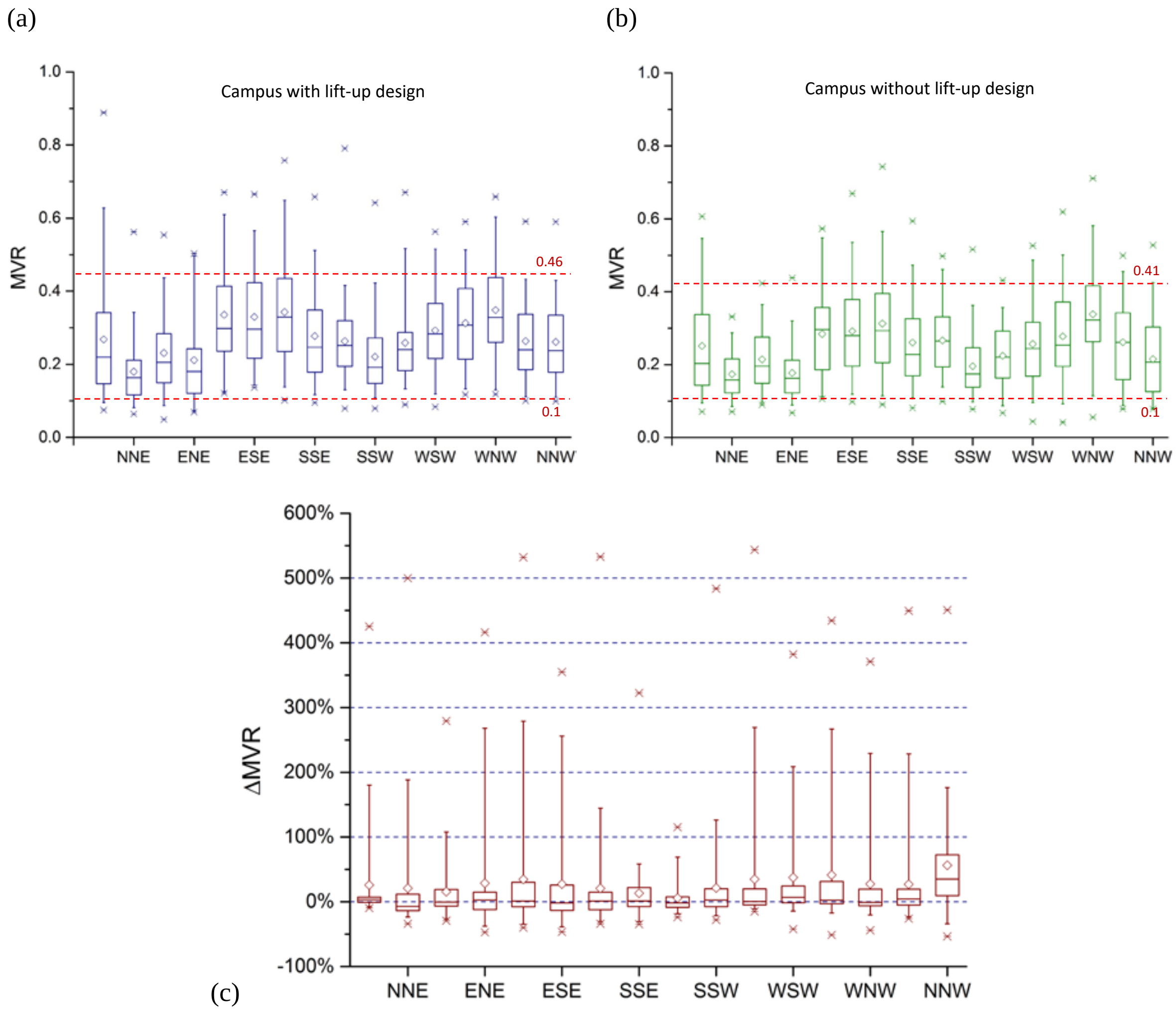


Fig.7. Box plots of MVR results in wind tunnel tests for 16 incident wind directions: the box edges represent the 25th and 75th percentiles, the whiskers for the 5th and 95th percentiles, the lines in the boxes for median values, and the symbols (◊) for mean values: (a) MVR values at pedestrian level with lift-up design; (b) MVR values at pedestrian level without lift-up design; (c) ΔMVR values at pedestrian level.

Even though Fig.7 can provide an overall and generalized picture of wind environment in the campus for 16 wind directions, considerably more efforts are required to interpret the effects of lift-up design on local wind environment. Hence, the polar plot of directional mean wind velocity change ratio is used here with respect to 16 approaching wind directions. The results of directional mean wind velocity change ratio for the three representative positions, which have been marked in Fig.5, are shown in Fig.8. The red shaded area indicates negative values of ΔMVR, which means that wind velocity will be higher when there is no lift-up design in the campus.

(a) (b) (c)

Fig.8. Results of directional mean wind velocity change ratio for three representative positions: (a) Position A; (b) Position B; (c) Position C.

The directional mean wind velocity change ratio of Position A (see Fig.5), which is surrounded by lift-up areas of DE wing (building between D core and E core) and EF wing (building between E core and F core), is shown in Fig.8 (a). It demonstrates that wind environment at this area is benefited from lift-up design for all approaching wind directions. Besides, significant “speed-up” effects can be observed at this position, and the values of ΔMVR frequently exceed the upper bound of 200% especially when the approaching wind comes from eastward and westward directions. Fig.8 (b) shows the values of ΔMVR for 16 wind directions at Position B (see Fig.5), which is surrounded by GH wing (building between G core and H core) and HJ wing (building between H core and J core). The values of ΔMVR are mostly negative except for approaching wind from southwest and west. It can be accounted for the fact that the horizontal approaching flow weakens the down wash flow from GH wing and HJ wing. This has also been explained in our previous study [15]. However, the decrease of MVR values are all within 50%. It can be seen from Fig.8 (c) that the values of MVR barely change because of the fact that Position C is located relatively far from the lift-up design in the campus. These findings in Fig.8 further support the idea that the wind environment at pedestrian level generally benefits from lift-up design in the campus. In addition to this, these results are in accordance with our previous studies that lift-up design can increase the wind velocity at pedestrian level [11, 13, 15], even for a complex urban environment.

4.2 Effects of lift-up design on thermal comfort

4.2.1 Monitored environmental parameter

In order to quantitatively assess thermal comfort in summer and winter, the instantaneous monitored environment parameters are summarized in Table 3. Noted that the daily average values of T_a, RH and T_{mrt} (indicated in bold letters) for four sample days are utilized to obtain PET values of the campus in this study. The values of PET are calculated by following the procedures presented in Section 3.3 and only the daily average monitored environmental parameter are used for obtaining values in summer and winter correspondingly.

Table 3. Summary of monitored environmental parameter for four sample days

Environmental parameters		Cloudy day in summer		Sunny day in summer		Cloudy day in winter		Sunny day in winter	
		Podium	Lift-up	Podium	Lift-up	Podium	Lift-up	Podium	Lift-up
Air temperature (T_a, ℃)	Max	32.1	31.9	33.5	31.9	21.9	21.9	25.8	24.8
	Min	31.6	31.7	32.4	30.8	21.0	21.2	24.4	23.3
	Average	**31.8**	**31.8**	**32.8**	**31.1**	**21.5**	**21.6**	**25.4**	**23.6**
Relative humidity (RH, %)	Max	72.0	71.0	88.8	88.0	71.0	72.0	58.0	63.0
	Min	69.0	70.0	80.6	78.0	65.0	65.0	54.0	57.0
	Average	**70.0**	**70.8**	**86.7**	**83.0**	**67.7**	**68.4**	**55.2**	**61.1**
Mean radiant temperature (T_{mrt}, ℃)	Max	45.3	34.2	65.1	32.3	31.8	23.6	57.8	25.5
	Min	41.1	32.3	53.0	30.6	27.0	21.9	48.2	23.0
	Average	**43.6**	**33.3**	**58.6**	**31.6**	**29.2**	**23.0**	**52.5**	**23.9**

4.2.2 Assessment results of thermal comfort in summer

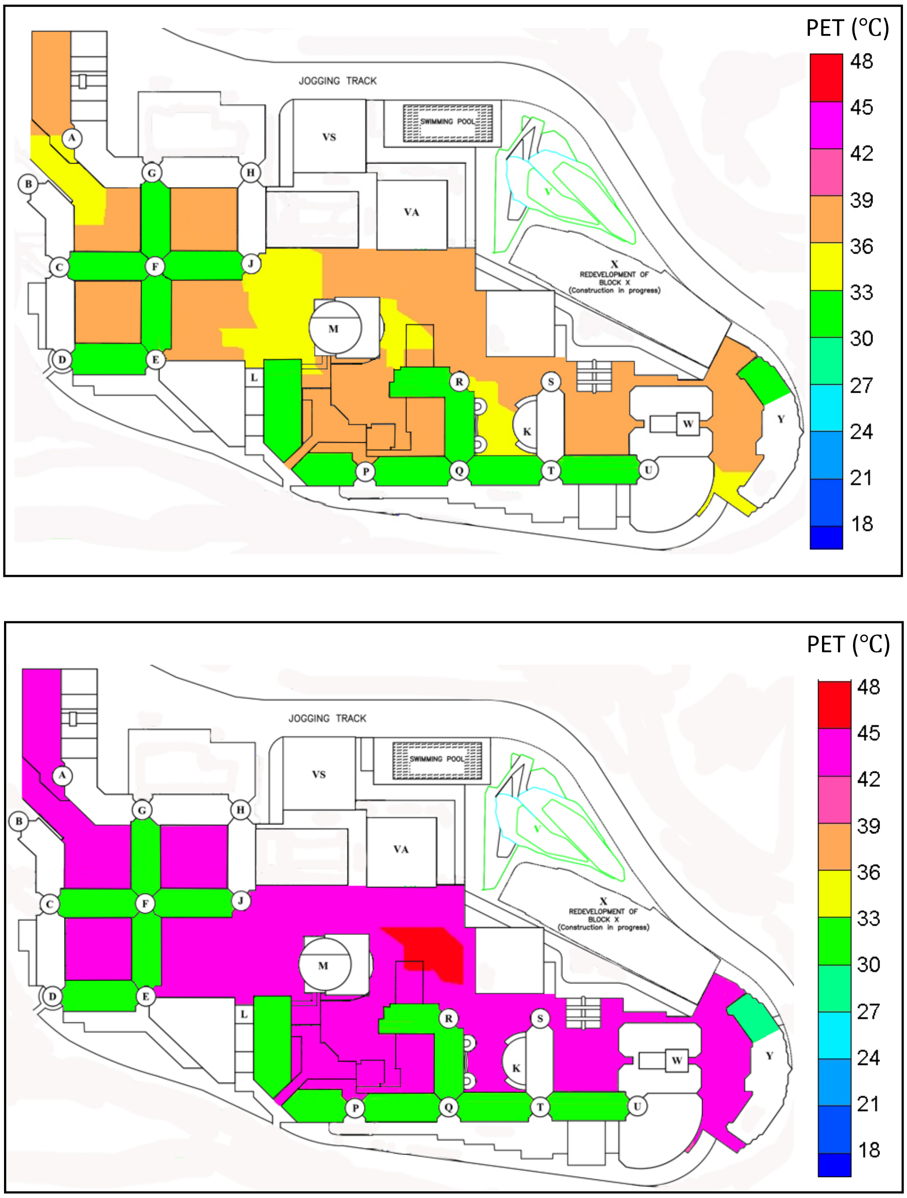
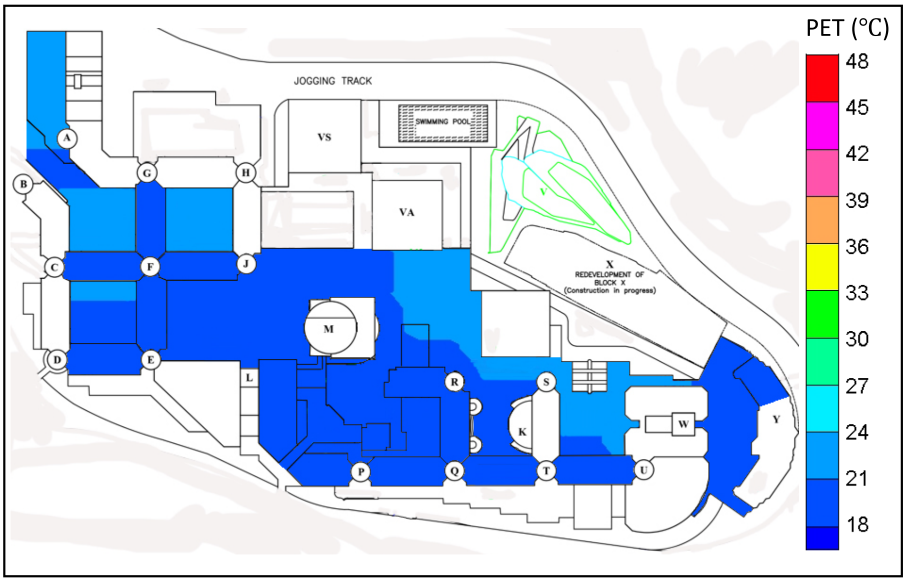


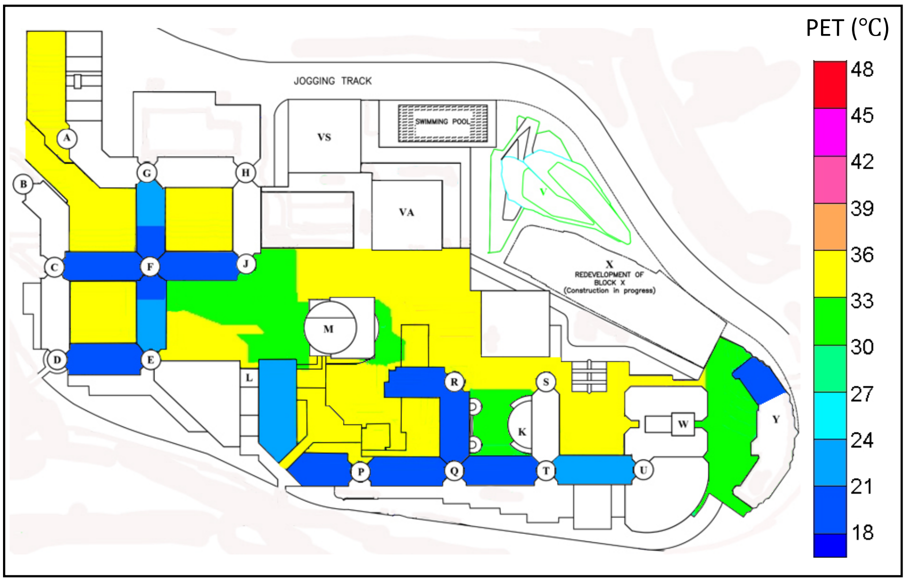
Fig.9. Pedestrian level thermal comfort assessment results in summer: (a) cloudy day in summer (Jul. 15, 2016); (b) sunny day in summer (Aug. 22, 2016).

The obtained PET results of the campus in summer are shown in Fig. 9: Fig. 9(a) presents the results of cloudy day in summer and Fig. 9(b) presents the results of sunny day in summer. It should be mentioned that the daily average monitored environmental parameters in the cloudy and sunny summer days are used to obtain the PET values presented in Fig. 9. What stands out in the figures is that the PET values in lift-up areas are between 30°C to 33°C in two different days. This indicates slight heat stress according to the definition of physiological stress on human beings in Taiwan as shown in Table.2. It means that pedestrians can do some activities in these lift-up areas even in hot and humid summer of Hong Kong, which can also provide a strong verification for our previous studies [11, 13, 15]. Besides, as shown in Fig.9 (a) the differences of PET values between podium area and lift-up area are mostly 6℃, which means a remarkable change in thermal perception according to Table 2. Moreover, Fig.9 (b) shows that PET values of the podium area are more than 42℃ in a sunny summer day and some places even exceed 42°C, which can be considered as extreme heat stress according to Table 2. However, the PET values in the lift-up area are between 30℃ to 33℃ at the same time due to the shading effect and higher wind velocity. The differences of the PET values between the podium area and the lift-up area are mostly over 12℃, which clearly demonstrates the extraordinary advantage of lift-up design in the subtropical urban cities, such as Hong Kong.

4.2.3 Assessment results of thermal comfort in winter



(a)



(b)

Fig.10. Pedestrian level thermal comfort assessment results in winter: (a) cloudy day in winter (Dec.6, 2016); (b) sunny day in winter (Dec. 12, 2016).

Fig.10 shows the PET results of the campus in winter: (a) cloudy day in winter (Dec.6, 2016); (b) sunny day in winter (Dec. 12, 2016). Noted that the daily average monitored environmental parameters in the cloudy and sunny winter days are used to obtain the PET values presented in Fig.10. It can be seen from Fig.10 (a) that there is no significant difference of PET values between lift-up area and podium area when it is cloudy in winter. The PET values of most places in the campus are within the range between 18°C and 21°C, which can be considered as "cool" by Taiwan range [48]. In addition, some places in the campus have relatively higher PET values (but below 24°C) because of lower wind velocity. In Fig.10 (b), it is apparent that PET values vary greatly: the highest PET values are above 33°C, and the lowest PET values are below 21°C. The difference of PET values between lift-up area and podium area in sunny day is evidently larger than that in cloudy days in winter. At least 6°C of PET differences exist in Fig.10 (b), which indicates remarkable thermal perception according to Table 2. It should be noted that the PET values of all the lift-up areas are over 18°C in winter days, which means that the lift-up design does not cause uncomfortable cold stress.

4.2.4 Effects of lift-up design on thermal comfort of podium areas

It is obvious that lift-up design can effectively reduce the heat stress in hot and humid summer while assures thermally comfort environment in winter from the assessment results of Fig.9 and Fig.10. Besides, our previous study found that it is wind velocity and solar radiation that contributes to remarkable differences of PET values [11]. In fact, Section 4.1 indicates that lift-up design can also change the wind environment of podium area significantly. In order to illustrate the effects of lift-up design on thermal comfort of podium areas, the PET values of podium area with and without lift-up design are presented in Fig.11. It should be mentioned that the values of OMV obtained from wind tunnel tests both with and without lift-up design are used as the input wind velocity data for calculating PET.

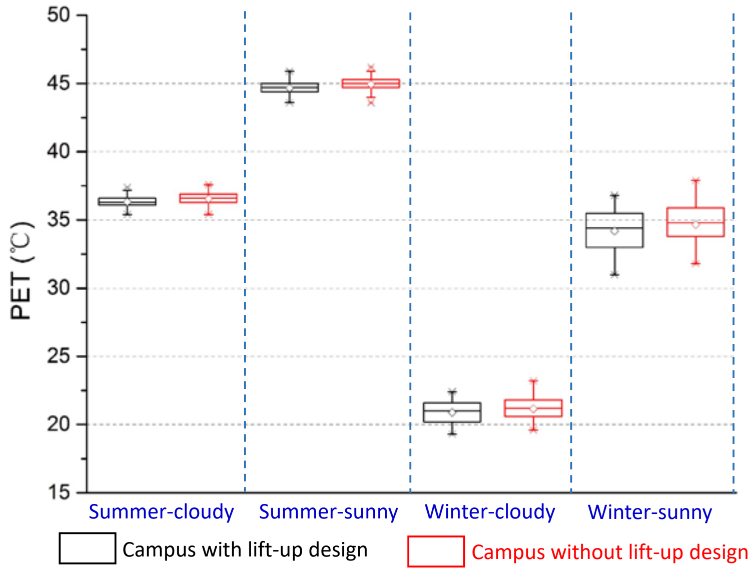


Fig.11. Box plots of podium PET results for four sample days with and without lift-up design: the box edges represent the 25th and 75th percentiles, the whiskers for the 5th and 95th percentiles, the lines in the boxes for median values, and the symbols (◊) for mean values.

It can be seen from Fig.11 that the results of PET in podium area without lift-up design are higher than that with lift-up design, which suggests that lift-up design in the campus can also contribute to reducing the heat stress of podium area. This can be explained by the fact that lift-up design can effectively improve pedestrian level wind environment in podium areas. This results further support the idea that lift-up design in the campus can contribute to the thermally comfort environment in the campus.

5. Conclusion

The aim of this study is to assess the effects of lift-up design on pedestrian level wind environment and thermal comfort in a complex urban environment. An integrated method is therefore proposed to represent thermal comfort conditions in summer and winter. The HKPolyU campus is chosen as the study area. The wind tunnel tests of HKPolyU campus model were carried out to obtain wind velocity in the campus; and the on-site measurements were conducted for four typical days to acquire environmental parameters. The measurement parameters are used as inputs to obtain PET values for achieving thermal comfort assessment in the campus. Besides, the effects of lift-up design on pedestrian level wind environment in the campus are also analysed in this study.

The main findings of the study are summarized as follows: (1) the proposed integrated method that combines wind tunnel technique and on-site monitoring approach can be used to predict outdoor thermal comfort. (2) The lift-up design in the campus can notably affect the pedestrian level wind environment both in the lift-up area and podium area. (3) The differences of thermal sensation between lift-up area and podium area are larger in sunny days than that in cloudy days. (4) The largest thermal sensation difference between the lift-up area and podium area occurs in the summer-sunny day while the smallest thermal sensation occurs in the winter-cloudy day. (5) The PET values in the podium areas become smaller without lift-up design than that with lift-up design in the campus. (6) The lift-up design can effectively improve the thermal conditions in the campus. In particular, it can provide a thermally comfortable microclimate even in a hot and humid sunny day in summer while not cause uncomfortable cold stress in winter.

In general, this study clearly indicates that lift-up design has a significant influence on pedestrian level wind environment and thermal comfort both in summer and winter. It should be noted that even though this study focuses on a university campus in Hong Kong, the methodology proposed in this paper can be applied to other similar cases. Meanwhile, this study also serves as a good demonstration of the integrated outdoor thermal comfort prediction method that combines wind tunnel test technique and on-site monitoring method. The final outcome of the study can be of value to improve the liveability and vitality of outdoor thermal comfort in urban cities.

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