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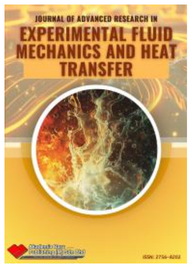

Wind Flow Dynamics Around High-Rise Buildings: Insights from Wind Tunnel Experiments

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ABSTRACT

Interaction between high-speed winds and urban buildings may contribute to unfavourable winds, safety risks, and building damage. This study aims to clarify the effects of high-rise buildings of UTM (Menara Razak-MR and Residensi Tower-RT) on the mean and turbulent wind speeds within the canopy layer and to develop a prediction model based on the wind tunnel experiment (WTE). Outdoor wind speeds are used as the input for conducting WTEs. In the wind tunnel, thermistors and hotwire sensors measure wind speeds at the selected canopy heights. Contour maps are used to present the analysis of the distribution of vertical profiles for both wind directions (22.5° and 202.5°) with high wind speeds. The spanwise uniformity flow has a standard deviation of less than 0.1 within the wind tunnel section. The wind profile is produced by a castellated block (25 mm cubic) of 17% packing density. The vertical profiles of approaching wind followed a power law index of 0.23, which falls within the suburban terrain category. The results show that wind speed u increases at a lower canopy layer in Plane 6 to Plane 8, and root mean square speed (u_{rms}) fluctuates in the downstream flow.

1. Introduction

In recent years, development in urban areas has gradually increased and intensified the density of the concrete jungle. High-rise buildings have contributed to local wind discomfort or disturbance towards pedestrians by deflecting strong winds to ground level [1]. The induced speed of strong winds by high-rise buildings within the canopy layer may not only damage public properties but also pose a danger to pedestrians. However, potential risks related to wind impacts due to high-rise buildings in urban areas are often overlooked. This is a significant concern since the wind distribution pattern during strong wind events varies due to the complex urban morphological features such as building geometry and arrangement. Thus, it is essential to understand the wind impact and its

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characteristics within the urban canopy layer, as severe wind events might lead to unfavorable accidents or losses (human safety or damage to infrastructure).

The urban canyon is usually found in a big city with a high density of tall buildings where the streets are surrounded by buildings. The features of the urban canyon are much more related to the change in microclimate. Thus, the evaluation during the urban planning and design stage is crucial to maximizing shelter, dispersion, urban warmth, and solar access [2]. Wind at the pedestrian level has been an essential aspect to be concerned about as the wind around buildings at a height of 1.5-2.0 m above ground may pose a risk to pedestrians [3] and has been gradually incorporated into urban planning and building design [4]. Generally, such wind studies have been conducted in countries that experience strong wind, and some developed well-established guidelines and criteria for pedestrian wind evaluation. Some local city authorities even requested a pre-assessment of the wind, which met the requirements before construction [5,6]. However, the assessment criteria code varies according to country rules and pedestrian activities.

By conducting the wind studies, locations at high risk of experiencing strong wind can be identified, and proper remedial measurements such as adding vegetation or canopies can be applied to reduce the hazard [7,8]. The comparison works between the current research and the existing prediction models proposed by Macdonald [9], Kubota *et al.,* [10], Ikegaya *et al.,* [11], Ahmad *et al.,* [12], Abd Razak *et al.,* [13], and Yuan *et al.,* [14], and for wind speed estimation, may reveal some additional valuable insights of the canopy wind characteristics which indirectly affecting the wind at pedestrian level. Yazid *et al.,* [15] conducted a sensitivity analysis to examine the impact of various parameters on wind flow patterns and pollutant dispersion within a simplified street canyon model. Roshezam *et al.,* [16] numerically analyze airflow in a SolidWorks-designed ventilation system, focusing on louver positions and slat angles of 15° and 30°. The results suggest that a 15° slat angle ensures smoother airflow with minimal turbulence, while a 30° angle increases inlet velocity and pressure, leading to greater turbulence and potential indoor climate issues.

Most of the previous studies implemented CFD simulations using generic building models for prediction purposes [17-22]. However, the precision of the prediction model requires a high level of parameter control procedure. Thus, comparing findings from this study is an excellent effort to reveal the compatibility of the previous model proposed in a realistic condition. In addition, the prediction model proposal is believed to significantly contribute to the literature because the findings may help predict rare wind events occurring in both wind directions (22.5° and 202.5°) within the canopy height near pedestrian level in the built environment.

2. Methodology

2.1 Target Site

The high-rise buildings in Universiti Teknologi Malaysia Kuala Lumpur (UTMKL) have been selected as the target site of this study due to its location in a densely populated area near the centre of Kuala Lumpur, the capital city of Malaysia, making it a representative sample. Two high-rise buildings were identified (our previous paper) [23] with strong wind in their vicinity, which are RT (94 m) and MR (Menara Razak) (84 m). Figure 1 shows the satellite image of the urban campus and the visual representation of the campus layout with respective building heights. Different colors represent the varying heights. The wind flow directions examined in this study are indicated by black arrows. Referring to Figure 1(b), the northern section of the campus mainly consists of low to medium-height buildings; there are low-rise buildings in the vicinity of Residensi Tower (RT) of UTMKL. As mentioned, the central area of interest is how the high-rise buildings influence the wind distribution patterns within the urban canopy layer. Thus, only high-rise buildings are considered to be the target buildings in this context.

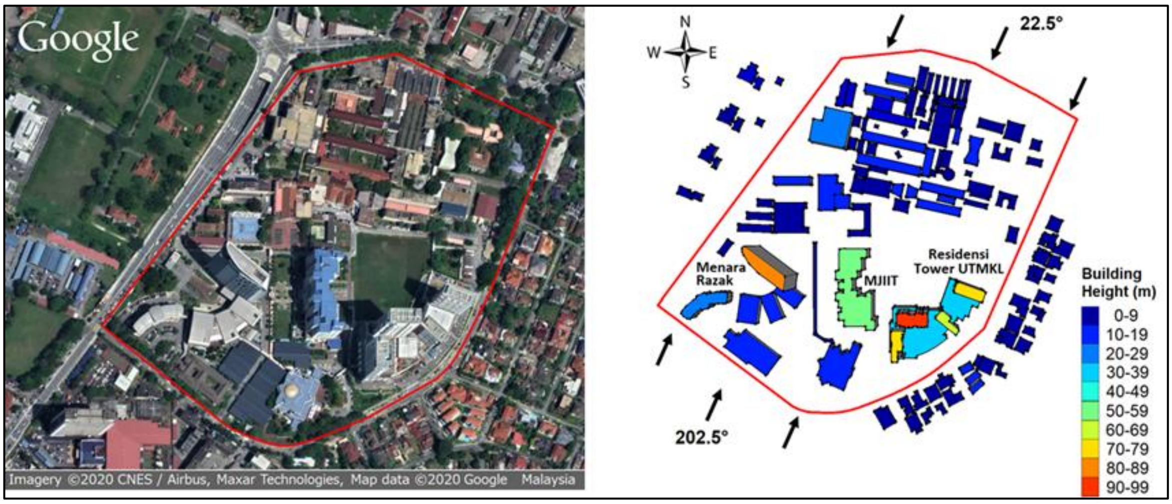


Fig. 1. (a) Satellite image of the UTMKL campus. The red line denotes the boundary of the campus (b) Campus layout and building heights

2.2 Wind-Tunnel Setup

The same closed-circuit wind tunnel for both wind directions (22.5° and 202.5°) having a turn table with a diameter of 1.28 m was considered in this study (employed in a previous paper) [24,25]. The scaled testing models (1:750) ensuring a capped blockage ratio of 3% [26] are prepared according to the exact building shapes and layout, imitating an accurate depiction of the actual urban environment to avoid overlooking the presence of noteworthy buildings [26]. The spanwise uniformity flow has a standard deviation of less than 0.1 within the wind tunnel section. A castellated block (25 mm cubic) of 17% packing density produces the wind profile. The vertical profiles of approaching wind followed a power law index of 0.23, which falls within the suburban terrain category.

In the present study, WTE is used to measure the wind velocity and the vertical profiles for the parameters; mean wind speed (u) and root mean square (u_{rms}) are used to reveal the effects of buildings using the scaled-down model with realistic geometry. The WTE has the advantage of considering different variations or perspectives during the planning stage of building construction. The flexibility of data collection at multiple positions in WTE allows researchers to obtain a more comprehensive monitoring database at a lower cost compared to implementing a similar layout in field measurement. The frequency distributions of the local reference wind speed are presented in the probability density function(s) (PDF) shown in Figure 2. Although the PDFs for mean and maximum wind speed are relatively low, with the mean of 1.47 m/s, the data are essential for wind analysis and are used extensively as the wind tunnel input for the WTE. Based on Figure 2, 'SD' represents standard deviation, and 'n' represents the amount of data.

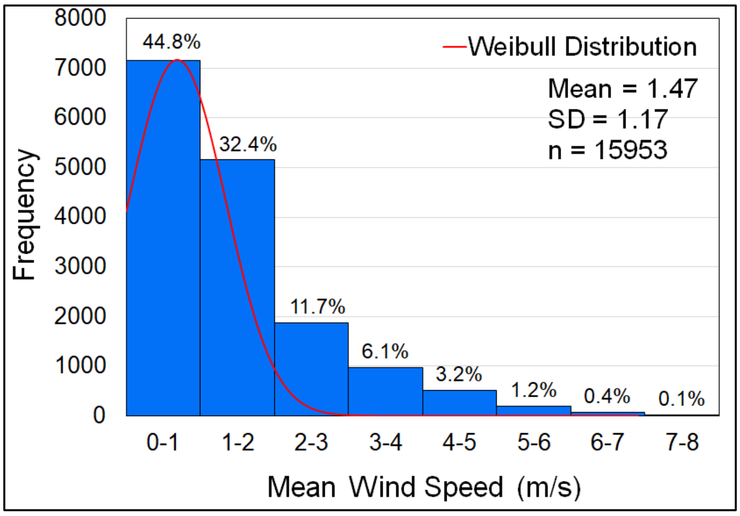
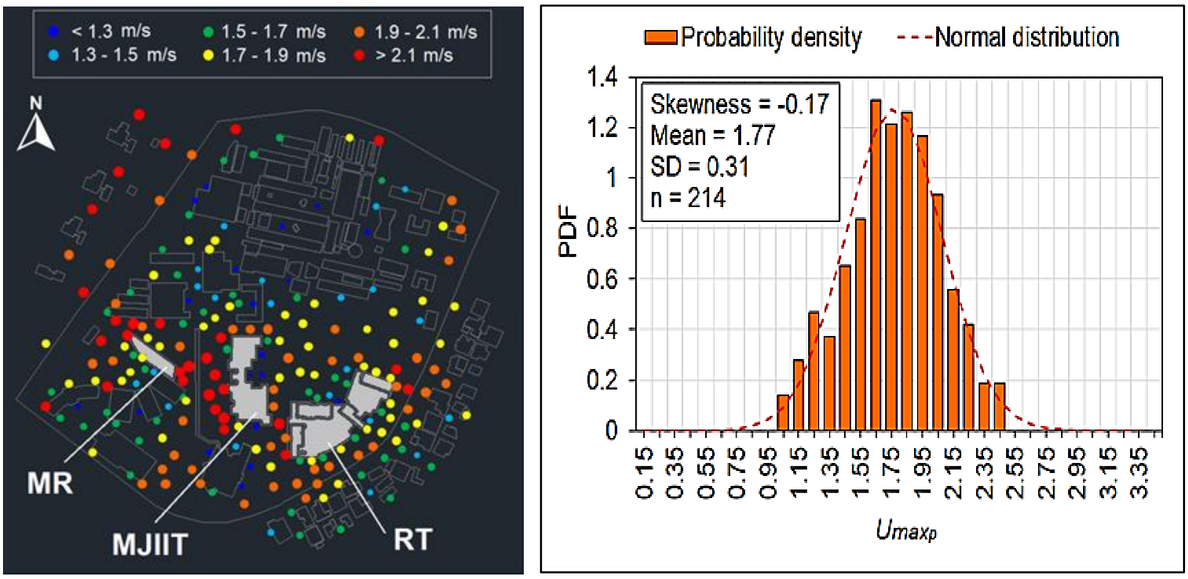


Fig. 2. Probability density function (PDF) of mean wind speed

2.3 Wind Speed Distribution with Various Wind Directions

Meanwhile, the wind distributions and PDFs of the maximum wind speed for the entire study region are displayed in Figures 3(a) and 3(b). ‘SD’ in 3(b) represents the standard deviation, and ‘n’ represents the number of data points. Referring to the wind speed distribution maps Figure 3(a), Most high-rise building proximity is associated with high mean wind speeds (red and orange dots represent the two highest intensity levels). Higher wind speeds are seen near the edges and corners of the MR and RT buildings. Since the testing models rely on actual geometry, there is a notable degree of heterogeneity in the high-speed regions.



(a) (b)

Fig. 3. Distribution of wind (a) The maximum wind speed within the campus area (b) The associated probability density functions (PDFs) of the maximum wind speed

According to Tamura *et al.,* [22], the location of the stagnation point gets higher at the windward site when the building height increases. This drives the strong winds towards the pedestrian level, intensifying the downdraught effect. This shows that the design and height of buildings significantly impacted raising wind speeds at the lower canopy height closer to the pedestrian level. The strong winds around high-rise buildings may be caused by the downdraught effect and the flow separation near the buildings [27]. The downdraught effect may also cause the occurrence of a jet near a building corner [28]. The results show that the maximum wind within the campus area is twice the mean wind speed.

Although it is interesting that the PDFs of the mean and maximum wind speeds (Figure 3(b)) closely follow the Gaussian distributions (denoted by the red lines), the distributions are slightly skewed in the negative values. This result implies that the magnitude of gust wind speeds is considerably more significant than the mean wind speed for the overall study region. However, the observations of strong wind speeds are limited in the campus area.

3. Results and Discussion

Using a logarithmic vertical axis, Figure 4 displays conventional PDFs of the wind speeds surrounding the MR and RT buildings in a logarithmic vertical axis. Based on Figure 4, SK and KT indicate the average skewness and average kurtosis for each of the wind speed categories, respectively. The solid line indicates the normal distribution. The wind speed data are classified into three divisions by the values. Black dots in the schematics at the right-up corner refer to the measurement points near the respective target buildings in wind directions of 22.5°.

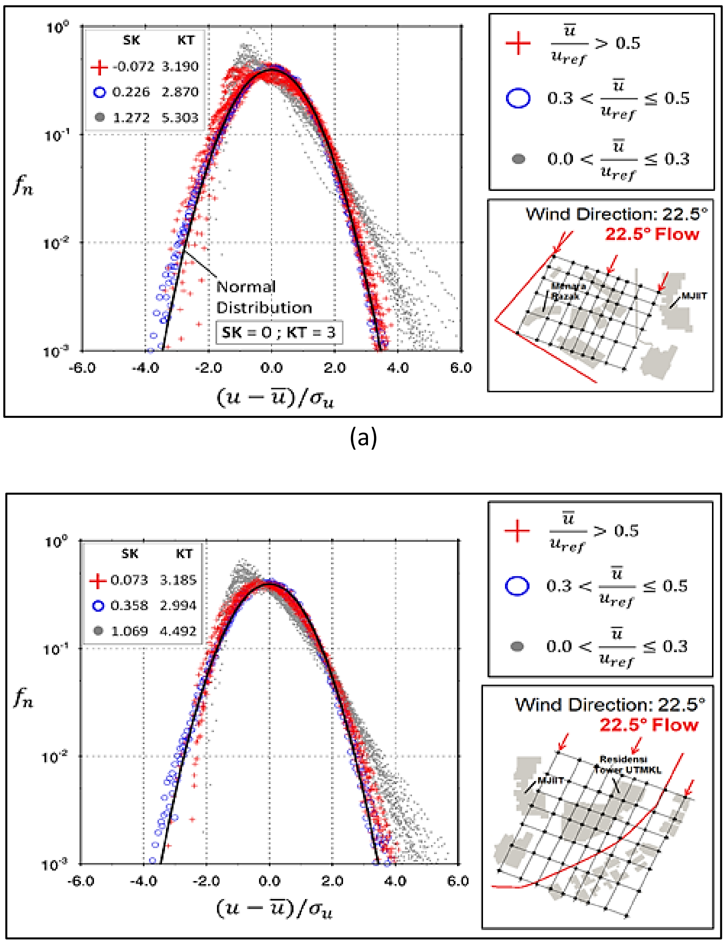
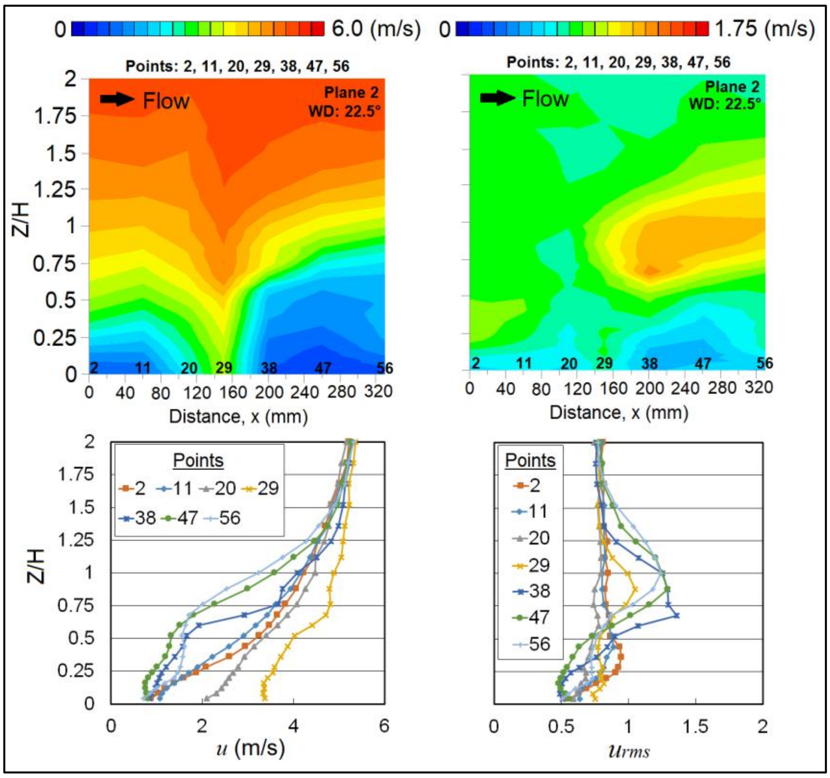


Fig. 4. Standardized probability density functions concerning wind speeds around (a) MR building (b) RT building

According to Figure 4, both wind speed PDFs exhibit the same tendency, independent of wind direction. The test values are classified into three wind speed divisions, and the hypothesis is that the peak factor can be predicted by the normal distribution when it is sufficiently large. In the graph, solid lines indicate normal distributions. In contrast, the results demonstrated that the PDFs were positively skewed and deviated from the normal distribution, indicating that the PDFs were consistent with the normal distribution. Averaging skewness (SK) and kurtosis (KT) for each wind speed category are the only data displayed in Figure 4 due to panel normalization based on mean and standard deviation for various positions. When the wind speed is high enough, KT approaches three, and SK approaches zero. This shows that the distribution is getting closer to a Gaussian distribution. This indicates that the distribution is getting closer to becoming a Gaussian distribution.

The venturi effect occurs at point 29, where the wind converges and flows through the two high-rise (MJIIT and RT) buildings. The speed-up winds are clearly shown from the vertical profile distribution of *u* in Figure 5(a), and its arms distribution is shown in Figure 5(b). Based on Figure 5, plane 2 (streamwise directions) within the canopy layer with Residensi Tower (RT) as the target building under the wind direction (WD) of 22.5°. The ordinate Z/H: Z is the canopy layer in the wind tunnel, normalized by H, the height of the target building model (125 mm). At the windward of the RT building (points 1 to 9), wind flows mostly depend on the approaching wind.

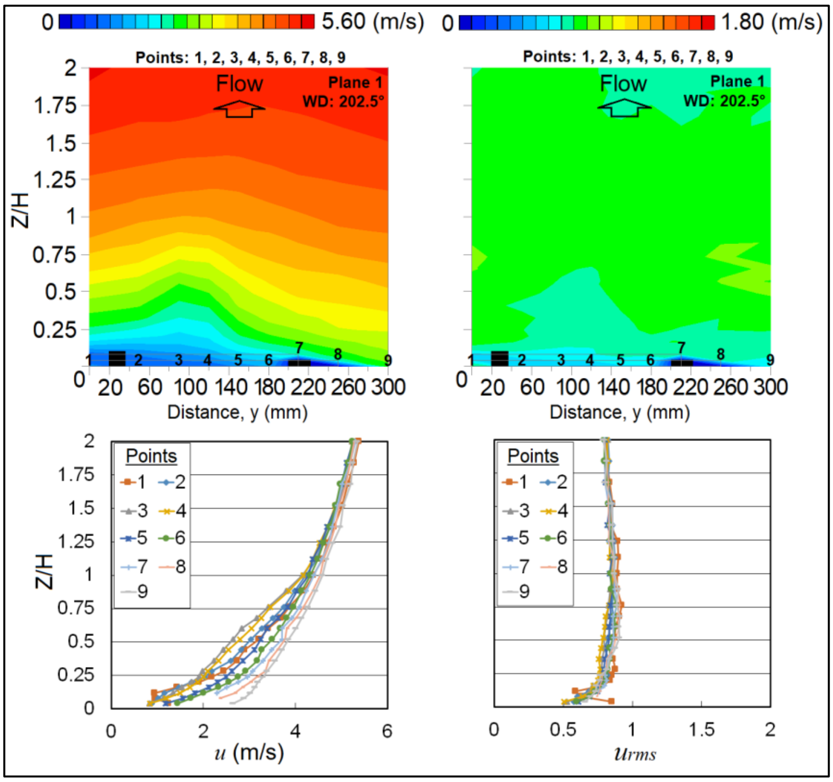


(a) (b)

Fig. 5. Vertical profiles (a) The mean wind speed, *u* (b) The root mean square, u_{rms} at X-plane

Focusing on the effects of the target RT building, the distributions of *u* near points 3 to 5 under the Y-plane (spanwise direction) are presented in Figure 6(a). Although the variation of *u* is not seen, the RT building might have a little effect causing the turbulence flow, due to the combined winds from downdraught and approaching wind, whereby these fluctuations can be observed from the vertical profile of u_{rms} as shown in Figure 6(b). According to Figure 6, plane 1 (spanwise directions) within the canopy layer with Residensi Tower (RT) as the target building under the wind direction

(WD) of 202.5°. The ordinate Z/H: Z is the canopy layer in the wind tunnel, normalized by H, the height of the target building model (125 mm)

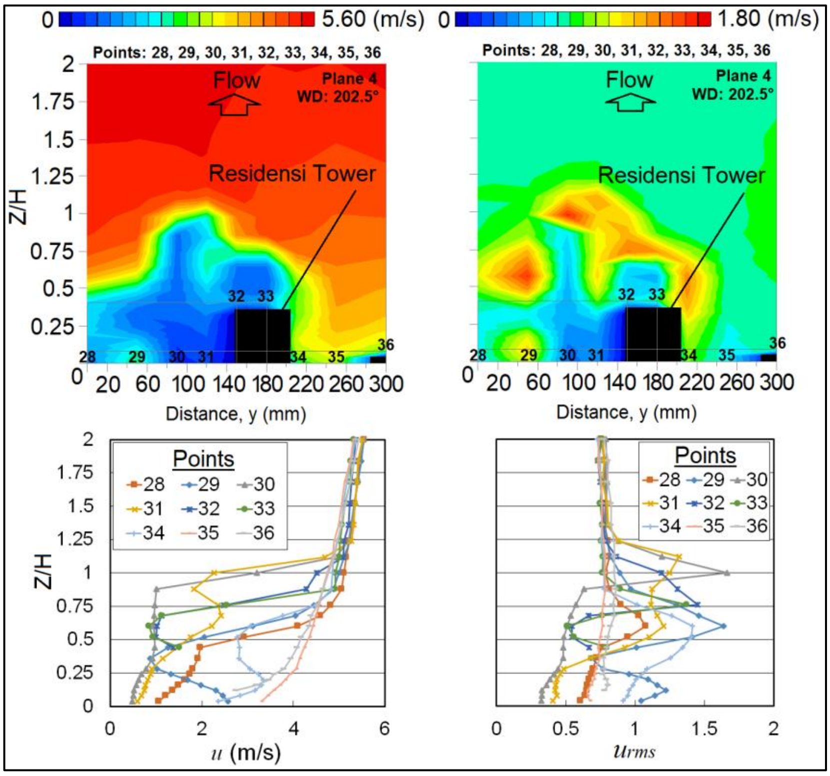


(a) (b)

Fig. 6. Vertical profiles (a) The mean wind speed, *u* (b) The root mean square, u_{rms} at Y-plane

Besides that, the surrounding low-rise buildings located near the RT building might also experience strong winds due to the curved shape of the RT building, which may speed up the approaching wind, causing a higher u at the lower ground near the region at points 25, 26, 34, and 35. Figure 7 shows the vertical profile distribution of u and u_{rms}, respectively, where plane 4 (spanwise directions) within the canopy layer with Residensi Tower (RT) as the target building under the wind direction (WD) of 202.5°. The ordinate Z/H: Z is the canopy layer in the wind tunnel, normalized by H, the height of the target building model (125 mm). When the speed-up flow passes through the open field, the wind speed may further increase, which explains the higher wind speed experienced at the surrounding buildings downstream.

Figure 8 shows the *u* distributions downstream, under the respective *Y*-plane(s) view (spanwise direction), from Plane 6 to Plane 8, where you are increasing at a lower canopy layer. The ordinate Z/H: Z is the canopy layer in the wind tunnel, normalized by H, the height of the target building model (125 mm). The flow fluctuations may have also extended downstream, as shown in the u_{rms} distribution in Figure 9. Based on Figure 9, the ordinate Z/H: Z is the canopy layer in the wind tunnel, normalized by H, the height of the target building model (125 mm).



(a) (b)

Fig. 7. Vertical profiles of (a) the mean wind speed, u, and (b) the root mean square, u_{rms} at Y-plane

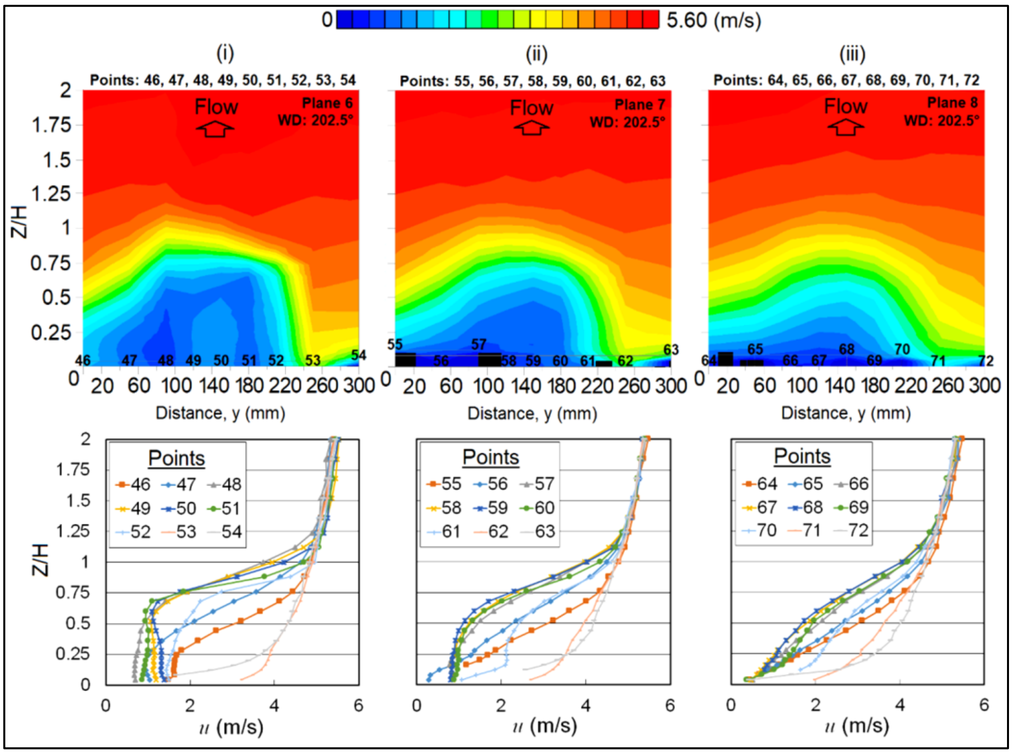


Fig. 8. Vertical profiles of the mean wind speed, u, at respective Y-plane(s) (spanwise directions) within the canopy layer with Residensi Tower (RT) as the target building under the wind direction (WD) of 202.5° (a) Plane 6 (b) Plane 7 (c) Plane 8

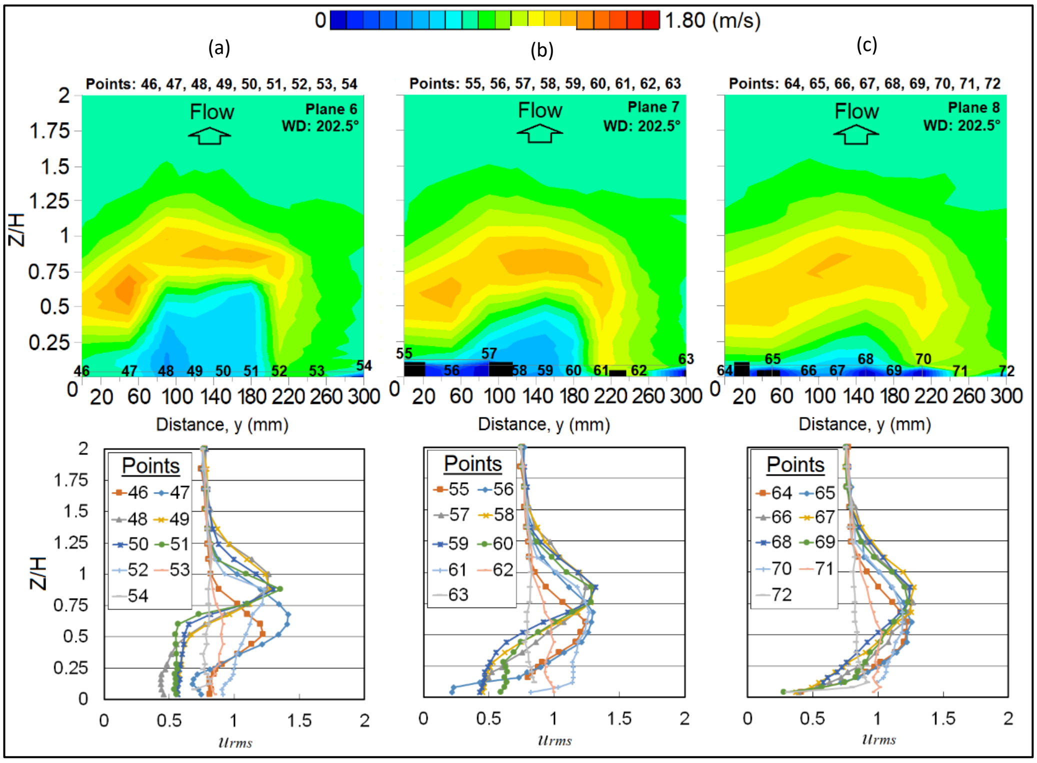


Fig. 9. Vertical profiles of the root mean square, u_{rms} at respective Y-plane(s) (spanwise directions) within the canopy layer with Residensi Tower (RT) as the target building under the wind direction (WD) of 202.5° (a) Plane 6 (b) Plane 7 (c) Plane 8

4. Conclusions

The results indicated that the wind distributions depend on the building's arrangement, corresponding to the wind incidences (22.5° and 202.5°). Speed-up winds are spotted at the windward of the building (downdraught effect) and the passage between the buildings (venturi effect). Besides that, the design of the buildings' corner edges may have contributed to the induced wind speed. Strong winds experienced at the RT building's podium regions might need attention to improve necessary precautionary measures. These findings may assist in pre-identifying the possible factors that should focus on during the planning stage to create a friendly environment for the communities. The results show that the exceeding wind speeds based on the peak factor of the normal distribution are plausible when mean wind speeds are sufficiently large (or with a threshold of $\bar{u}/u_{ref} > 0.3$) in the wind direction.

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