

Simultaneous multi-point measurement and analysis of wind speed at pedestrian height in urban canopies with high-rise buildings using PIV

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Simultaneous multi-point measurement and analysis of wind speed at pedestrian height in urban canopies with high-rise buildings using PIV

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1. INTRODUCTION

Urban winds can dramatically change and fluctuate in time. These fluctuations create environmental hazards. A well-known example is "building wind", which indicates strong gusts generated around high-rise buildings. These winds can cause walking difficulty, safety risks, and even damage to building structures. To manage these challenges effectively, it is important to accurately assess wind environment and then implement appropriate countermeasures. Some municipal governments have a regulation requiring the assessment to quantify the impact of new high-rise buildings on the surrounding wind environment. For the assessment, on-site measurements, wind-tunnel experiments, and computational fluid dynamics approaches are commonly employed.

In wind-tunnel experiments, scale models are employed and exposed to artificially generated urban-like turbulent flow. Accordingly, hot wire and thermistor anemometers were used to evaluate the average wind speeds around the models. The present wind assessment procedures are based on the averaged wind speeds to identify the strong wind speed regions. Although outdoor wind velocity distributions are temporally turbulent and spatially inhomogeneous, such effects on the environment are not well considered because of scarcity in the measurement techniques to determine instantaneous wind speeds at multiple locations.

To understand strong wind phenomena caused by high-rise buildings and to take the turbulent effects into account, fundamental studies are required on developing measurement techniques of instantaneous wind speeds at multiple points and analyzing the spatial structure of airflow. Therefore, the purpose of this study is to experimentally measure wind speed distributions with high frequency at a pedestrian height within urban canopy layers, including high-rise buildings.

2. EXPERIMENT

Wind-tunnel experiments using particle image velocimetry (PIV) were conducted to measure instantaneous wind speeds at a pedestrian height within simplified urban building arrays to quantify the effect of high-rise buildings. PIV is an advanced measurement technique determining spatial velocity distributions based on the visualized fluid motion by tracking the movement of tracer particles dispersed in airflow. These particles are illuminated by laser sheet, and the reflection of the light was captured using a high-speed camera with very high frequencies.

Scaled building models representing urban building arrays were placed on the floor of the wind-tunnel test section. Each model was constructed using cubes with a side length of 0.1m. The building height is denoted as H . The models were arranged in a staggered pattern with a 25%

building packing density. The model array consisted of 34 and 14 rows in the streamwise and lateral directions, respectively. The 28th row from the upstream edge was defined as the measurement area. To investigate the impact of surrounding building heights, especially of high-rise buildings, on the wind environment, three different model configurations were used. Case 1.0H consists of uniform height blocks of **1.0H**. Case 1.5H and Case 3.0H include a high rise building of among the building arrays consisting of uniform height blocks of **1.0H** (Figure 1).

Figure 1 illustrates the optical and measurement system. The laser sheet was projected parallel to the wind-tunnel floor as follows. First, the laser passed through two cylindrical lenses to sharpen the diameter. Additionally, the beam was expanded using a laser line generator. The sheet was projected to the area in front of the high-rise building. A high-speed camera, installed below the wind tunnel, was used to capture the particle images. The frame rates of the image capturing is set to be 2000fps to 4000fps depending on the approximated wind speeds in the measurement area.

For the data analyses to determine the velocity distribution, PIV software (Seika Digital Image, Koncerto II ver. 2.1.33.22 / 2.2.37.33) was employed. The interrogation size was set to be $32 \times 32 \text{ px}^2$ (approximately $7 \times 7 \text{ mm}^2$) with the 50% overlap of the areas. After adjusting the captured images to be suitable for the PIV analysis, the multi-grid method was employed to determine the displacement of the interrogation areas.

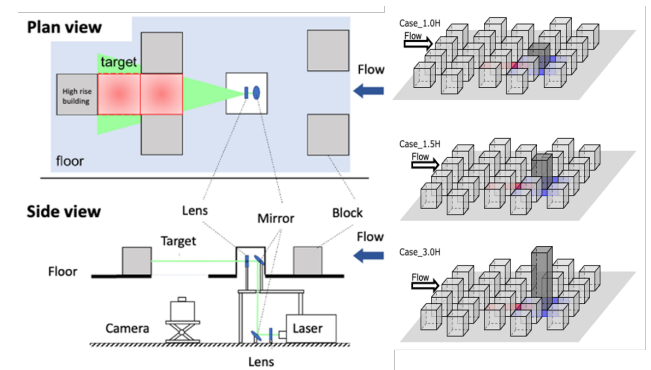


Figure 1 Experimental system and models

3. RESULTS

Figure 2 shows time averaged distribution of streamwise velocity component $\bar{u}$ with the vectors for each case. Case 1.0H is represented by Figure 2(a), Case 1.5H by Figure 2(b), and Case 3.0H by Figure 2(c). The wind speed is normalized by the reference wind speed U_{ref} . U_{ref} is defined as the free stream wind speed measured by a Pitot tube installed outside the boundary layer. In general, the reverse flow regions expand in the streamwise direction

as the building height increases. In addition, the reverse flow region becomes larger than the streamwise flow in Case 3.0H. These findings indicate that reverse flow regions have a significant impact on the pedestrian-level wind environment, especially as building height increases.

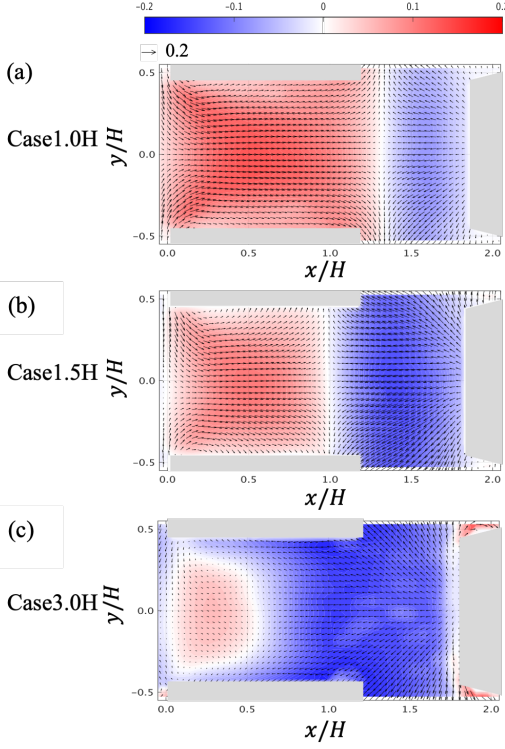


Figure 2 Time averaged distribution of streamwise velocity component $\bar{u}$ at $z = 0.1H$

Figure 3 shows the relationship between the F-percentile wind speed $u_{h,F}$ on the vertical axis and the average wind speed $\bar{u}_h$ on the horizontal axis to examine plausible gust factors GF for all cases. GF is defined by the ratios of $u_{h,F}$ and $\bar{u}_h$. The average and F-percentile wind speeds are normalized by U_{ref} . Comparing the GF reference lines with the data, most wind speeds for the 90th and 99th percentiles fall within $GF < 3$. On the other hand, majority of the 99.9th percentile wind speeds exceed 3.0. These findings suggest that the common GF range of 2 to 3 may underestimate the peak values when the 99.9th percentile wind speeds are used as representative strong wind speeds. Furthermore, in Case 3.0H, 99.9th percentile wind speeds exceeding $GF > 5$ were also observed.

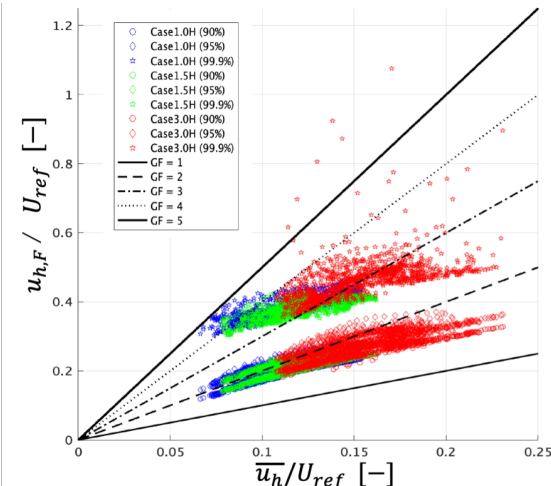


Figure 3 Relationship between average wind speed and percentile wind speed for each case

To clarify the statistical features of the wind speed, the PDFs u_h were analyzed. The standardized random variables are defined as follows.

$$\xi = \frac{u_h - \bar{u}_h}{\sigma_{u_h}} \quad (1)$$

Here, σ_{u_h} indicates the standard deviation of u_h .

Figure 4 shows the PDFs of Case 1.0H, Case 1.5H, and Case 3.0H. The grid points covered the range of $(x/H, y/H) = (0.0, -0.4)$ to $(1.7, 0.4)$ at intervals of 0.1. The values at the specified locations were averaged. The distributions for each case are classified into three categories based on the magnitude of the average wind speed: high-speed regions ($\bar{u}_h/U_{ref} > 0.135$), medium-speed regions ($0.11 < \bar{u}_h/U_{ref} < 0.135$), low-speed regions ($\bar{u}_h/U_{ref} < 0.11$). The distribution in high-speed regions is closer to the Gaussian distribution compared to medium-speed and low-speed regions. Additionally, across all cases, the distribution in low-speed regions shows significant positive skewness compared to high-speed and medium-speed regions. From these observations, it can be inferred that at points with higher average wind speeds, the PDFs of wind speed tends to approach the Gaussian distribution.

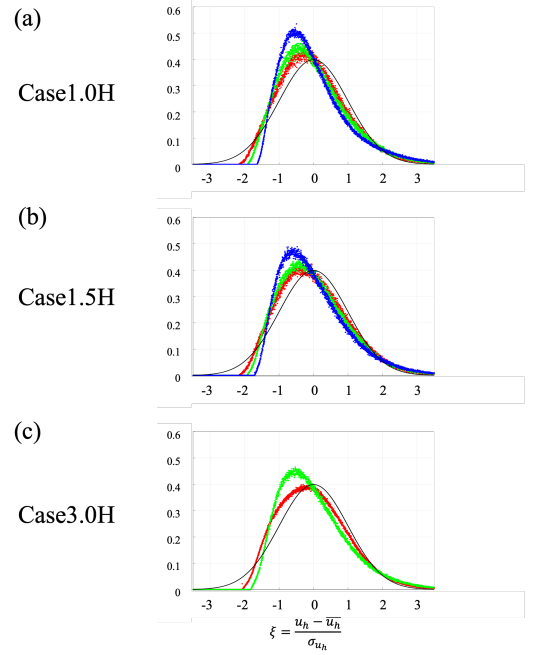


Figure 4 Probability density function of u_h in the range from $(x/H, y/H) = (0.0, -0.4)$ to $(1.7, 0.4)$ at $z=0.1$ for each case

4. CONCLUSIONS

The experimental data obtained in this study serve as a valuable resource not only for analyzing turbulence characteristics within urban canopies, including high-rise buildings, but also as a high-quality validation database for CFD simulations and instantaneous wind speed predictions. These findings enhance the understanding of pedestrian level wind environments and contribute to improving wind environment assessments.

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