Wind Engineering Joint Usage/Research Center
FY2025 Research Result Report

Research Field: Outdoor Environment
Research Year: FY2025
Research Number: 24242015
Research Theme: Comparative study of 2D flow field between its real-scale and lab-scale in an urban boundary layer

Representative Researcher:

Budget [FY2025]: 200,000JPY

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1.Research Aim

With the continuous progress of society and the rapid development of cities, a large number of buildings have been constructed, and buildings have become the main symbols of cities. The flow field environment around them affects people's production and life, such as wind loads on urban environmental buildings, wind field interference between buildings, pollutant diffusion within cities, drone flight within building complexes, and wind energy research, all of which are closely related to the wind field around buildings. In recent years, people have become increasingly interested in the natural air flow around cities and buildings.

Over the past few decades, wind tunnels have been regarded as a reliable method for determining wind loads on building complexes and other structures because they can reproduce the wind conditions in which buildings are immersed. Hui Y[1] studied the interference effect between two high-rise buildings through pressure tests on a 1:400 scale building model and particle image velocimetry (PIV) tests on a 0.03m × 0.03m × 0.12m building model in a wind tunnel. Watkins S[2] conducted computational and experimental studies on the flow around a 40-meter-high rectangular building in a 1/100 scale wind tunnel test, demonstrating that computational fluid dynamics can provide path planning for drone flight within buildings. However, the complexity of real atmospheric flow conditions cannot be fully reproduced in wind tunnels, and the limited space dimensions of wind tunnels lead to significant differences in Reynolds numbers between the object and the scaled model. Studies have shown that even when the flow around a building reaches the critical Reynolds number, the flow characteristics are still significantly affected by the Reynolds number effect, resulting in differences between full-scale and model[3]. Therefore, the suggestion of using larger-scale models or conducting tests in full-scale buildings is increasingly supported[4][5].

However, full-scale experiments in the current research on air flow around buildings are rare because they rely on expensive equipment, require a lot of time and effort, and are subject to uncontrollable meteorological conditions. Some existing full-scale measurements are still conducted using cup anemometers, ultrasonic anemometers, and four-hole pressure probes, which are cumbersome and provide limited data with low resolution in a single measurement, and cannot accurately reflect the flow field information around the entire building. In the field of wind energy research, Doppler lidar systems have been used to obtain wind speed, turbulence, wind direction turning, and wind shear data, but they are subject to certain measurement limitations around buildings: the test area should be located more than 10 meters above the lidar top, the scanning disk limits the distance at which the lidar can be placed on the side of the building, and the sampling rate is low, etc. [6]. Conventional particle image velocimetry (DPIV) can obtain high spatiotemporal resolution flow field measurements. However, due to the poor particle traceability at large scales, insufficient laser intensity, and camera resolution, instantaneous flow field DPIV measurements cannot be applied to areas larger than 5 meters, and the DPIV results of average flow field stitching have not been reported for areas larger than 10 meters, which is nearly two orders of magnitude smaller than the sampling area required in the field of wind energy, and far from meeting the needs of related research and industry.

At present, the commonly used field measurement methods of large-scale flow characteristics, such as acoustic radar and optical radar, can only measure single or multiple points, and the spatio-temporal resolution is low, which is difficult to quantify the complex turbulent flow in the atmosphere. Particle image velocimetry (PIV) has become a popular non-interventional experimental fluid mechanics measurement means, which can measure the entire two-dimensional or three-dimensional flow field synchronously and instantaneously[7]. With high spatiotemporal resolution, PIV is the only experimental method that can provide instantaneous fluid vorticity and strain rate information in rapidly changing fluids[8]. Hong et al.[9] used natural snowfall as a tracer particle to measure the actual flow field of wind turbines, which greatly exceeded the measurement range of PIV measurement, and only a single camera could achieve 100-meter level flow field measurement. Inspired by Hong et al. in view of the complexity of the shape and size of snowflake particles, the non-uniformity of atmospheric flow and the complex interaction between particle flow fields, researchers in this paper further modified the fluidness of snowflake particles and developed a set of large-scale two-dimensional flow field measurement methods for natural snowfall tracing[10]. Details of experimental measurement methods can be found in reference[10].

Based on the two-dimensional flow field measurement method of LPIV with snowflake tracing, this paper conducts on-site measurements of the full-scale building flow field and compares the differences with the experimental results in the wind tunnel. It provides new ideas and more detailed flow field data than previous studies for the measurement of the full-scale building flow field, and is of great value for the research and evaluation of the accuracy of wind tunnel scale experiments on building flow fields.

2.Research Method

2.1 Full scale LPIV measurement

The principle and system composition of traditional PIV is shown in Figure 2-1. The tracer particles uniformly spread into the flow field move along with the flow field, and are illuminated by the sheet light curtain generated by the laser through the optical lens. Finally, the camera of the light curtain in the opposite direction records the image, so as to obtain the timing diagram of the particle flow (double frame/single exposure mode). The velocity of the flow field can be determined by cross-correlation calculation of the particle image query window under the condition of known time interval between frames. The basic principle of LPIV for snowflake tracer is similar to the traditional PIV principle, but for the former, due to the complex shape of snowflake particles, the flow performance is not as good as that of traditional tracer particles, such as oil droplets, helium filled bubbles, etc., so it is necessary to revise the results after cross-correlation calculation. Since cross correlation calculation as the basic principle of PIV has been widely studied, this paper will not repeat, only describe the basic method of LPIV flow field snowflake follow-up correction.

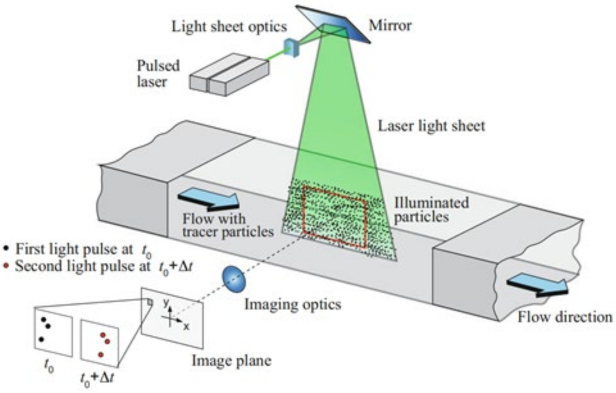


Figure 2-1 Basic Principle of Particle Image Velocimetry Measurement

The experimental site and equipment are shown in Figure 2-4. The experiment was deployed on the roof of the Electronic Factory Building of Harbin Institute of Technology at midnight on December 25, 2023. The measurement location was relatively flat, and there were several buildings and some tall trees nearby that blocked the view. The large-scale light curtain was generated by a spotlight through a reflector. In the actual measurement, at a distance of 50 m from the light curtain, the thickness of the light curtain was 600 mm to ensure that most snowflake particles could be recorded between consecutive frames. At the same time, a three-degree-of-freedom adjustable support was used to ensure that the light curtain was perpendicular to the horizontal plane. The particle images captured were in the same vertical plane. The main image acquisition device was the DJI Phantom 4 PRO V2.0 drone (equipped with a gimbal camera), and the frame rate and exposure time of the camera needed to match the flow field speed under study.

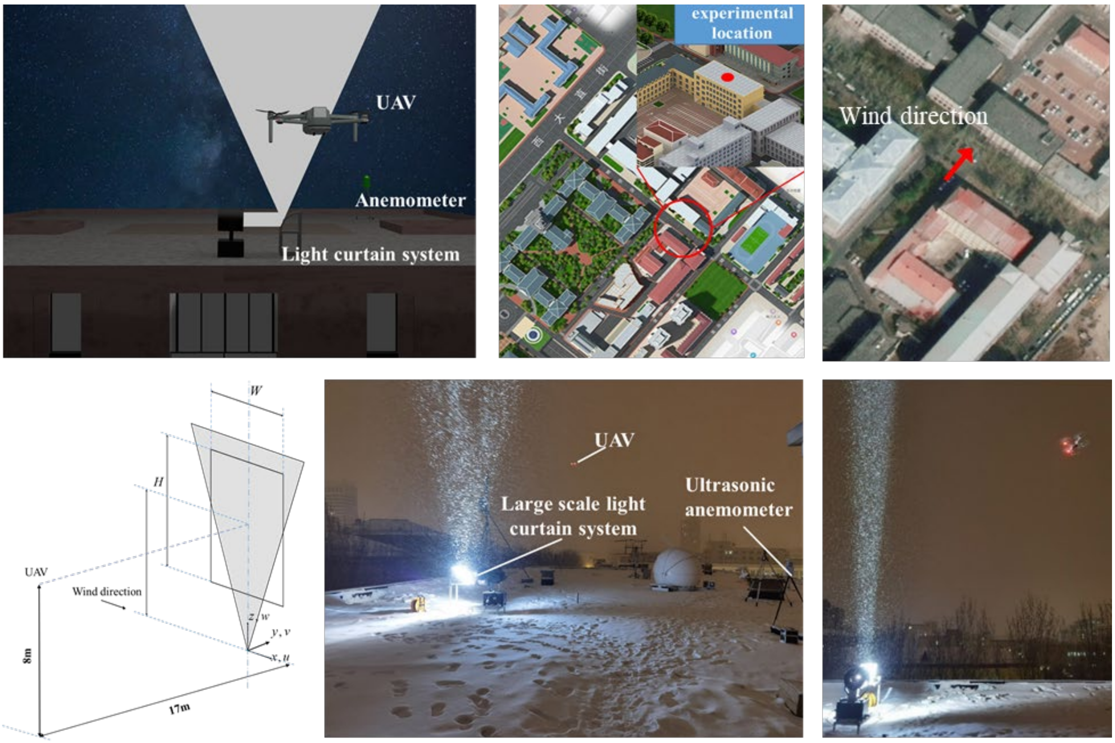


Figure 2-4 Experimental schematic diagram and actual field conditions

2.2. Wind Tunnel Scale Model Experiments

The wind tunnel scale-down experiments were carried out using the traditional PIV method. In a small-scale wind tunnel with a measurement section size of 1.2 × 9.37 × 1.0 m, wind tunnel experiments of buildings at a scale of 1/200 were completed. Three different wind speeds of 0.8 m/s, 1.2 m/s, and 1.6 m/s were set as the incoming flow to compare the influence of Reynolds number differences. The tracer particles in the wind tunnel experiments were olive oil droplets (with a particle size distribution of 1-5 μm), and FASTCAM Mini AX200 high-speed cameras with a resolution of 1024×1024 were used to collect images.

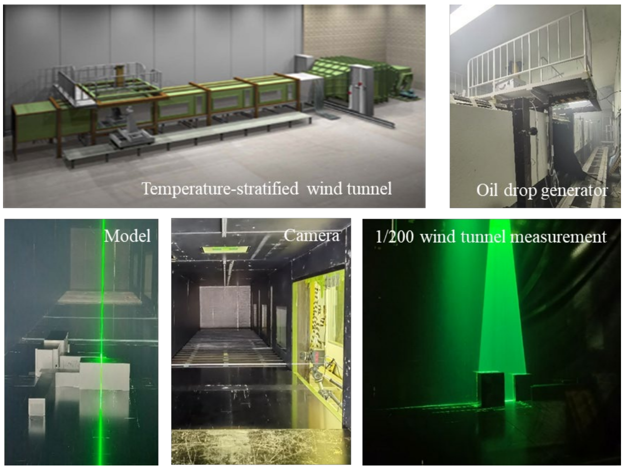


Figure 2-5 Reduced-scale wind tunnel and related experimental equipment

In the wind tunnel experiment, straight steel bars with a spacing of 20 cm and a height of 3 cm were used to increase the roughness of the wind tunnel ground, in order to simulate the real near-surface boundary layer of the atmospheric flow as closely as possible, as shown in Figure 2-5. The average wind speed profile was fitted by the exponential law:

$$U\left(z\right)=U_r\left(z/z_r\right)^{\alpha} \tag{2.4}$$

In the formula, U_r represents the wind speed at the reference height z_r above ground; α is the roughness exponent of the ground surface, whose value is related to the category of ground roughness. According to the "Code for Loads on Building Structures" (GB50009-2012) of China, for urban areas of cities with dense building clusters, the roughness exponent α = 0.22. Considering the influence of the complex terrain near the measured locations at full scale, ground roughness needs to be tested in multiple groups around 0.22. Figure 2-6 shows the wind profiles of four wind speeds of 0.8m/s, 1.2m/s, 1.6m/s, and 2m/s reconstructed. The ground roughness exponents calculated are approximately 0.24, 0.22, 0.20, and 0.17 respectively. From the turbulence intensity diagram, it can be seen that the turbulence intensity at 2m/s is basically consistent with that of the full-scale incoming flow, and the turbulence intensity at 2m/s is higher than that of the previous three wind speeds.

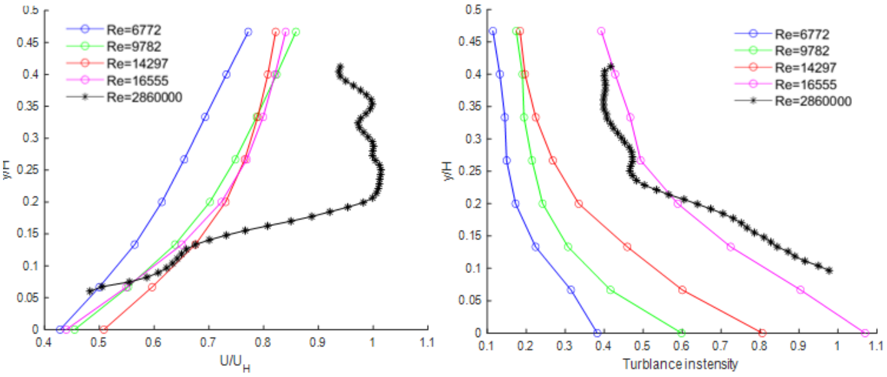


Figure 2-6 Average wind speed profile and turbulence intensity

2.3.Full-scale Measurement and Reconstruction of Flow Field in Reduced-scale Wind Tunnel

2.3.1.2.3.2.Flow Field Reconstruction

To obtain the velocity of the particles, this study uses the open-source particle image velocimetry (PIV) program PIVlab for post-processing of the particle images. PIVlab is a free toolbox and application used for processing the image data of PIV [13].

This study uses the recommended settings of the program: the cross-correlation selects the FFT window deformation algorithm, and the snowflake particle images are analyzed in two channels (the query window is 128 pixel × 128 pixel and 64 pixel × 64 pixel, with 50% overlap, and the second channel will eventually generate a velocity point in a 32 pixel × 32 pixel area): the first channel uses a relatively large query area to reliably calculate the displacement of the image data to obtain a good signal-to-noise ratio and strong robustness of cross-correlation; in the second channel, the size of the query window is reduced to obtain high vector resolution, and the offset and deformation of the query area in the second pass are performed by using the displacement information from the first pass.

The time-averaged two-dimensional velocity cloud maps of 3600 images finally obtained are shown in Figure 2-9. It can be seen that the obtained atmospheric flow field is relatively smooth with fewer singular points. This algorithm can be well used to process the snowflake particle images and reconstruct the flow field with a resolution of approximately 0.138 m. Here, it is assumed that the average velocity of about 7 particles in a 32 pixel × 32 pixel window represents the velocity of a single particle in this area, that is, it is assumed that the 7 particles have the same flow characteristics. Considering the size of the local vortex structure in large-scale measurements, the 32 pixel × 32 pixel velocity window is sufficient to describe it.

Settings used for the wind tunnel experiment processing: The cross-correlation adopts the FFT window deformation algorithm. The snowflake particle images are analyzed in two channels (the query window is 64 pixel × 64 pixel and 32 pixel × 32 pixel, with 50% overlap, and the second channel will eventually generate a velocity point in a 16 pixel × 16 pixel area). As in the above analysis, this size of the velocity window is sufficient to describe the flow.

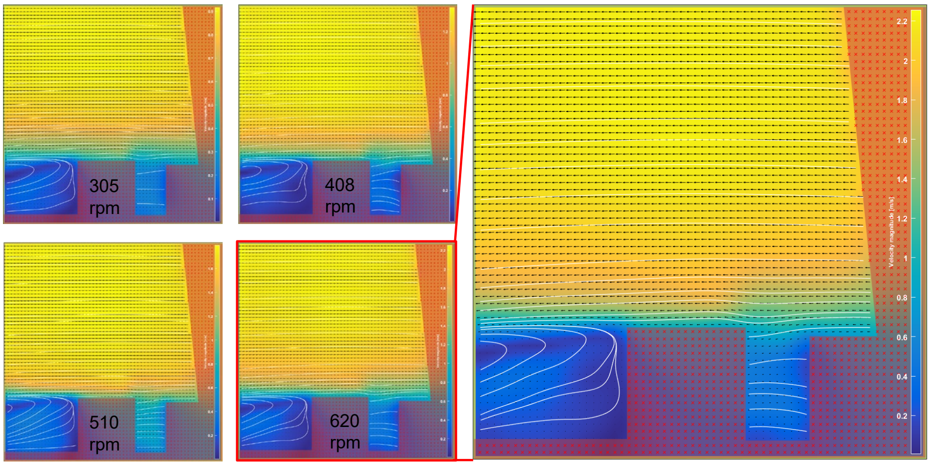
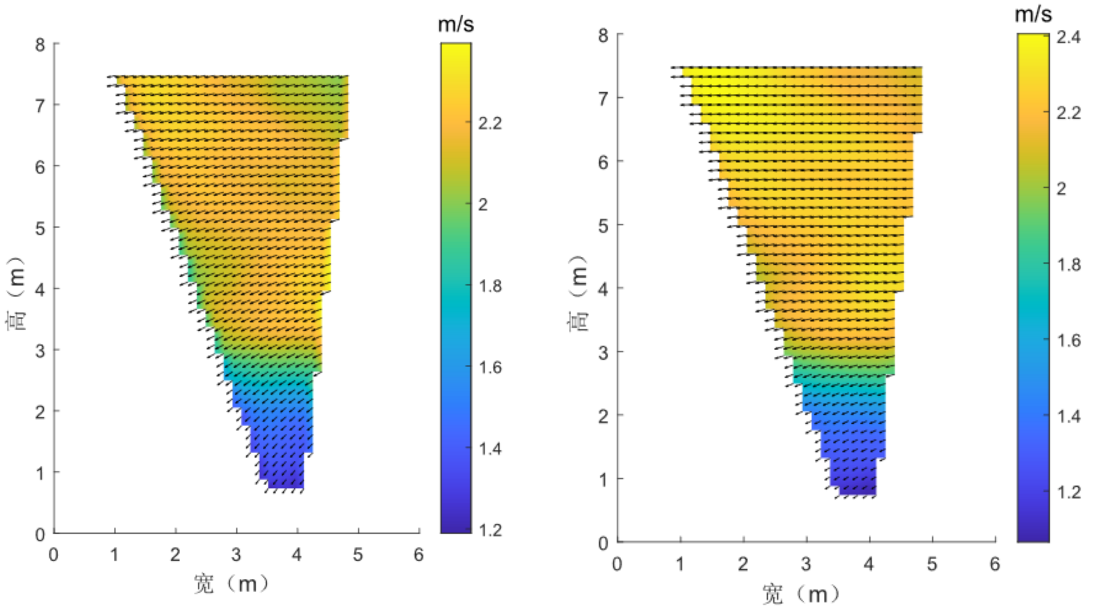


Figure 2-10 Result of time-averaged flow field reconstruction

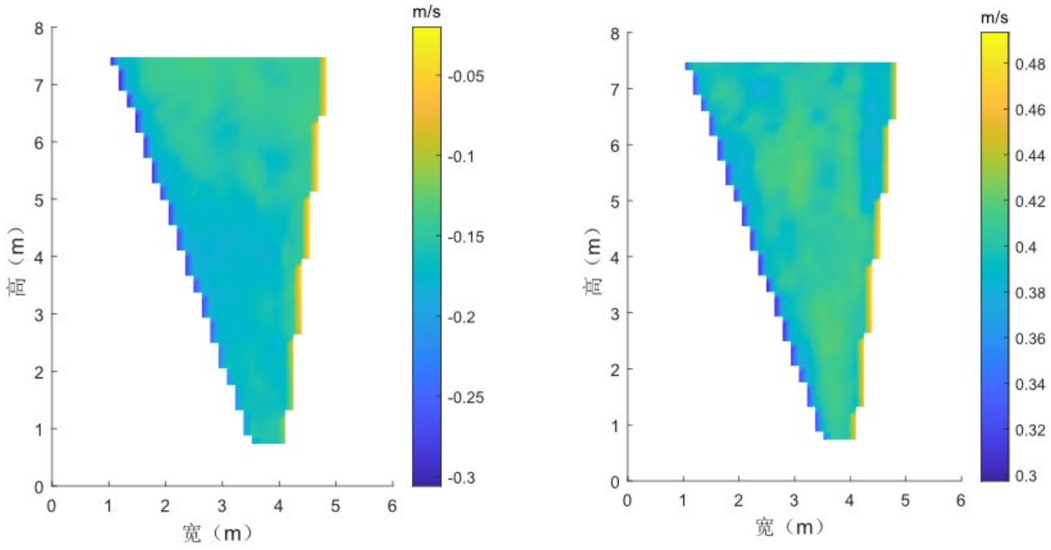
3.Research Result

Based on the above correction equations and the relevant physical property parameters of snowflake particles, the correction equations were solved according to the full-scale measured results. The particle velocity corresponding to the particles was extracted from the particle images calculated by PIV. The final correction effect is shown in Figure 3-1. From Figure 3-2, it can be seen that the vertical velocity of the mean flow field before and after correction has changed significantly. After the gravity influence was corrected, the velocity gradually tended to be horizontal.



（a） Before correction　　（b） After correction

Figure 3-1 Comparison Chart of Time-Average Flow Field Results



（a） Horizontal velocity difference cloud chart　　（b） Vertical velocity difference cloud chart

Figure 3-2 Comparison Chart of Velocity Difference Before and After Correction

From the data in Figure 3-2,it can be seen that both the horizontal and vertical velocities of the time-averaged flow field diagrams before and after the correction have changed. Due to the certain lag in the movement of snowflake particles in the flow field, the flow velocity slightly decreases after reconstructing the particle flow field, and the horizontal velocity increases after the correction. In the vertical direction, due to the significant influence of gravity on snowflake particles, there is an overall downward movement trend in the overall situation, resulting in an increase in the downward velocity. After the correction, subtracting this influence, the downward velocity decreases. Overall, the difference in velocity values before and after the correction is relatively uniform. It can be easily seen from the small difference in velocity values before and after the correction that the gravitational influence of snowflake particles is significant at this time, and snowflakes have a certain lag in following the flow phenomenon. The velocity cloud diagrams before and after the correction reflect the flow field situation after eliminating the force acting on snowflake particles, and it can be considered that this corrected image is the velocity cloud diagram of the background flow field.

As shown in the figure, the processing results of the wind tunnel experiment are presented, corresponding to the time-averaged flow field diagrams (left) and instantaneous flow field diagrams (right) under four different rotational speeds. Through processing the results of the wind tunnel experiment, it can be seen that the two-dimensional flow field vector diagrams of the flow field under different wind speeds are relatively similar. This may be because the flow field at the lowest rotational speed of 305 rpm corresponds to a wind speed of 6772, which has entered a fully developed turbulent state. At this time, the inertial effect of the fluid plays a dominant role under high Reynolds numbers, making the flow field insensitive to changes in wind speed. Compared with the full-scale results, it can be found that there are differences in the flow field at the bottom of the red triangular area in the full-scale flow field. In the full-scale flow field, the vertical direction of the flow field is downward, which may be due to the presence of trees higher than the building height at the upwind side of the building in the full-scale experiment, causing interference to the flow field. In the wind tunnel experiment, this model was not added, resulting in a difference in the flow field.

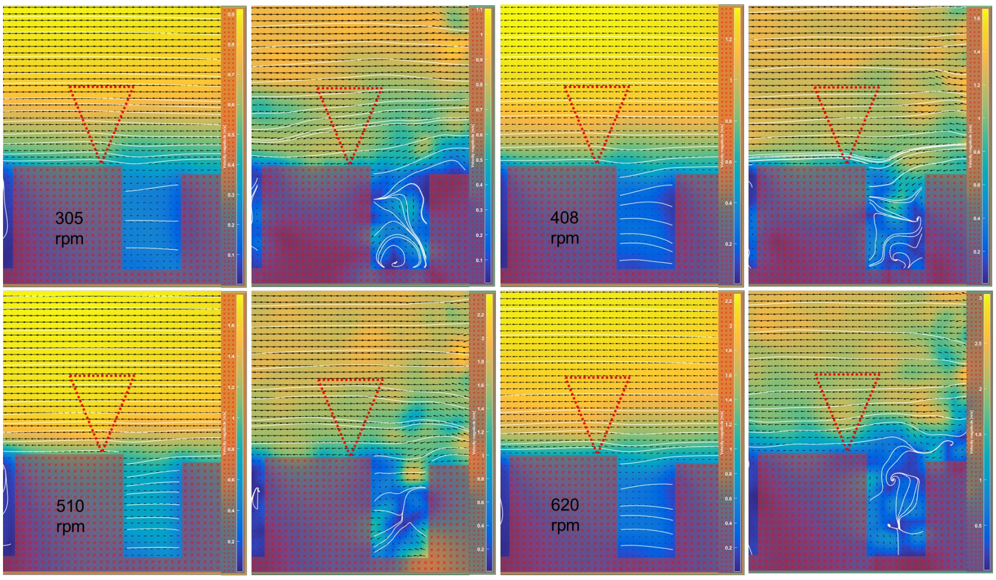


Figure 3-3 Average flow field and instantaneous flow field of wind tunnel experiment treatment

A comparative analysis of the wind profile and turbulence intensity between full-scale experiments and wind tunnel experiments reveals that in the scaled-down wind tunnel model, when the Reynolds number exceeds the critical value Re > 11000, the velocity distribution of the wind profile and the turbulence characteristics exhibit significant Reynolds number independence. Through dimensionless wind profile analysis, it is found that the curves under different Reynolds numbers have a high degree of overlap (Figure 2-6). This phenomenon can be attributed to the dominance of inertial forces at high Reynolds numbers and the weakening of viscous effects. Although the scaled-down model exhibits self-similarity at high Reynolds numbers, its results still have significant differences from the full-scale measured data. The full-scale wind profile has a faster velocity recovery rate in the vertical direction and a higher turbulence intensity than most wind tunnel data, and the degree of coincidence with the turbulence intensity at 620 rpm is relatively high. This difference may be due to the difficulty of the wind tunnel model in fully replicating the full-scale flow field (with complex building distribution within the city) and the surface details of the structure (such as vegetation and building textures); the full-scale atmospheric boundary layer contains multi-scale turbulent structures and thermodynamic effects, while the wind tunnel simulation cannot fully simulate the incoming flow conditions; even if the Reynolds number of the wind tunnel reaches the critical value, there is still a magnitude difference in the turbulent micro-scale between the full-scale and the wind tunnel.

Based on the above conclusions, the future experimental improvement directions are: within the allowable range of equipment, try to increase the test Reynolds number to approach the true state of the full-scale flow, and reduce the errors caused by Reynolds number mismatch; adopt a composite turbulence generation strategy, such as superimposing rough elements (such as sharp-angled arrays) at the wind tunnel inlet to make the turbulence intensity and wind profile match the full-scale measured values.

4. Conclusion

This paper adopts the LPIV method based on the tracking of snowflake particles to correct the flow field according to the forces acting on the snowflake particles and takes into account the influence of their complex shapes. It successfully obtains two-dimensional high-resolution measured flow field data at the top of the entire-scale building. The building model is scaled down for wind tunnel experiments to obtain the flow field at the corresponding position on the top of the entire-scale building. Further, the entire-scale data is compared with the wind tunnel scale-down experiments, and the following conclusions are drawn:

1. The Reynolds number independence of the wind profile in the scale-down wind tunnel is quite obvious. When the Reynolds number is greater than 11,000, the profile basically remains unchanged.

2. The entire-scale contour under high Reynolds numbers has a significant difference from that in the wind tunnel. The entire-scale vertical direction recovers faster and has stronger fluctuation.

3. The turbulence intensity in the wind tunnel is positively correlated with the Reynolds number. When the Reynolds number reaches the critical value, the turbulence intensity is close to that of the large-scale, and further comparison is needed.

4. It is recommended to conduct experiments under as high a Reynolds number as possible, and to increase the turbulence intensity in the wind tunnel.

5.References

[1] Hui Y , Tamura Y , Yoshida A , et al. Pressure and flow field investigation of interference effects on external pressures between high-rise buildings[J]. Journal of Wind Engineering & Industrial Aerodynamics, 2013, 115:150-161.

[2] Watkins S , Mohamed A , Fisher A , et al. Towards Autonomous MAV Soaring in Cities: CFD Simulation, EFD Measurement and Flight Trials[C]// International Micro Air Vehicles Conference & Flight Competition. 2015.

[3] Lim H C, Castro I P, Hoxey R P. Bluff bodies in deep turbulent boundary layers: Reynolds-number issues[J]. Journal of Fluid Mechanics, 2007, 571: 97-118.
[4] Moravej M. Investigating scale effects on analytical methods of predicting peak wind loads on buildings[J]. 2018.
[5] Cheng X X, Zhao L, Ge Y J, et al. Full-Scale/Model Test Comparisons to Validate the Traditional Atmospheric Boundary Layer Wind Tunnel Tests: Literature Review and Personal Perspectives[J]. Applied Sciences, 2024, 14(2): 782.
[6] Lim K E W , Watkins S , Clothier R , et al. Full-scale flow measurement on a tall building with a continuous-wave Doppler Lidar anemometer[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2016, 154:69-75.
[7] YAMAMOTO F, ISHIKAWA M. A Review of the Recent PIV Studies—From the Basics to the Hybridization with CFD[J/OL]. Journal of Flow Control, Measurement & Visualization, 2022, 10(04): 117-147.
[8] RAFFEL M, KOMPENHANS J. Theoretical and experimental aspects of image-shifting by means of a rotating mirror system for particle image velocimetry[J/OL]. Measurement Science and Technology, 1995, 6(6): 795.
[9] HONG J, TOLOUI M, CHAMORRO L P, et al. Natural snowfall reveals large-scale flow structures in the wake of a 2.5-MW wind turbine[J/OL]. Nature Communications, 2014, 5(1): 4216.
[10] Zhou Deli, Li Biao. Study on large-scale two-dimensional flow field measurement method via natural snowfall tracer. [D]. Harbin Institute of Technology, 2022.
[11] Zivkovic Z. Improved adaptive Gaussian mixture model for background subtraction[C]//Proceedings of the 17th International Conference on Pattern Recognition: Vol. 2. ICPR, 2004: 28-31.
[12] Uke G, Rajput A. Contrast Enhancement Technique of Dark Blurred Image[J]. 2006.
[13] Thielicke W, Sonntag R. Particle Image Velocimetry for MATLAB: Accuracy and enhanced algorithms in PIVlab[J]. 2021, 9(1): 12.

6.Published Paper etc.

[Underline the representative researcher and collaborate researchers]
[Published papers]
1.
2.
[Presentations at academic societies]
1. The First Academic Symposium on Flow Field Testing and Analysis Technology，2024.5.25-26，Harbin, China
2. Seminar of Academic Visiting to The Cyprus Institute, 1 Oct - 7 Oct 2024, Cyprus
[Published books]
1.
2.
[Other]
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7. Research Group

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8．Abstract (half page)

Research Theme
Representative Researcher (Affiliation)

Based on the LPIV two-dimensional flow field measurement method using snowflake tracer, this paper conducts on-site real-time measurement of the flow field of full-scale buildings and compares the results with those from wind tunnel experiments. The results show that when the Reynolds number in the scaled-down wind tunnel exceeds 11,000, the wind profile contour remains basically unchanged, demonstrating Reynolds number independence; however, at high Reynolds numbers, the full-scale wind profile shows significant differences from that in the wind tunnel, and the full-scale vertical velocity recovery is faster. The turbulence intensity in the wind tunnel increases with the Reynolds number, and it approaches the full-scale level at the critical Reynolds number. In the future, experiments can be conducted at higher Reynolds numbers and the turbulence intensity in the wind tunnel can be increased to better simulate the full-scale flow field. This study provides new ideas and more detailed flow field data than previous studies for the measurement of the flow field of full-scale building, and is of great value for the research on the flow field of buildings and the evaluation of the accuracy of wind tunnel scaled-down experiments.