Wind Engineering Joint Usage/Research Center
FY2022 Research Result Report

Research Field: Outdoor environment
Research Year: FY2022
Research Number: 22222010
Research Theme: Research on large-scale two-dimensional flow field measurement method via natural snowfall trace

Representative Researcher: LI Biao, MAO Shengli, XUAN Yingli

Budget [2022 FY]: Yen 60,000

*There is no limitation of the number of pages of this report.
*Figures can be included to the report and they can also be colored.
*Submitted reports will be uploaded to the JURC Homepage.

1. Research Aim

This research breaks through the limitation of particle image velocimetry measurement scale and uses naturally falling snow to provide persistent and environmentally friendly tracer particles, achieving non-intrusive flow field visualization measurement at sub-hundred-meter scale.

- Large-scale measurement experiment

This research specially designed a large-scale experimental subsystem to ensure its workability and smooth operation in complex outdoor meteorological environments. The experimental site selection and deployment were discussed to establish a large-scale particle image velocimetry experiment plan.

- Large-scale measurement flow field correction

This research used numerical simulation to predict and establish a drag coefficient correction model for snow particles. Based on the relationship between particle and fluid interaction forces, the connection between the background flow field and the particle velocity field was established. The overall correction improved the accuracy of the flow field to reflect the real flow situation.

The development of large-scale two-dimensional and three-dimensional instantaneous flow field visualization measurement technology is crucial. It can be used for aerodynamic experimental measurement around full-size advanced equipment and can be further extended to building measurement, such as bridges and high-rise buildings, to research the coupling effects between the near-surface atmosphere and buildings, verify numerical calculation models, and improve building aerodynamic layout performance.

2. Research Method

2.1 The large-scale experiment

2.1.1 Experimental system

To achieve non-intrusive visualization measurement of flow fields at sub-hundred-meter scales, this research designed and built a matched outdoor experimental platform, as shown in Figure 2-1 of the field test. It is mainly composed of a large-scale optical screen system, tracer particles (natural snow particles), a photography system, an outdoor mechanical movement system, and a power supply device.

Figure 2-1: Diagram of large-scale speed measurement experimental device

2.1.2 **Field Experiment Implementation**

Particle image velocimetry requires that experiments be carried out in areas with a dark background light environment and no building obstruction at night to obtain better image data and reduce background noise interference. The final experimental location was selected as shown in Figure 2-2, which is located on the edge of the city with few high-rise buildings and light interference, making it a good location for conducting experiments. The actual measurement scene is shown in Figure 2-3.

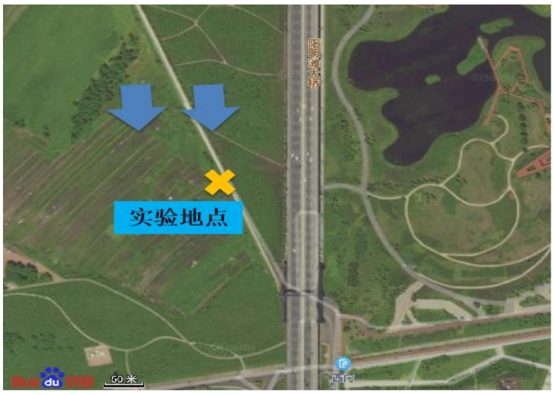


Figure 2-2: Satellite image of the experimental location vicinity

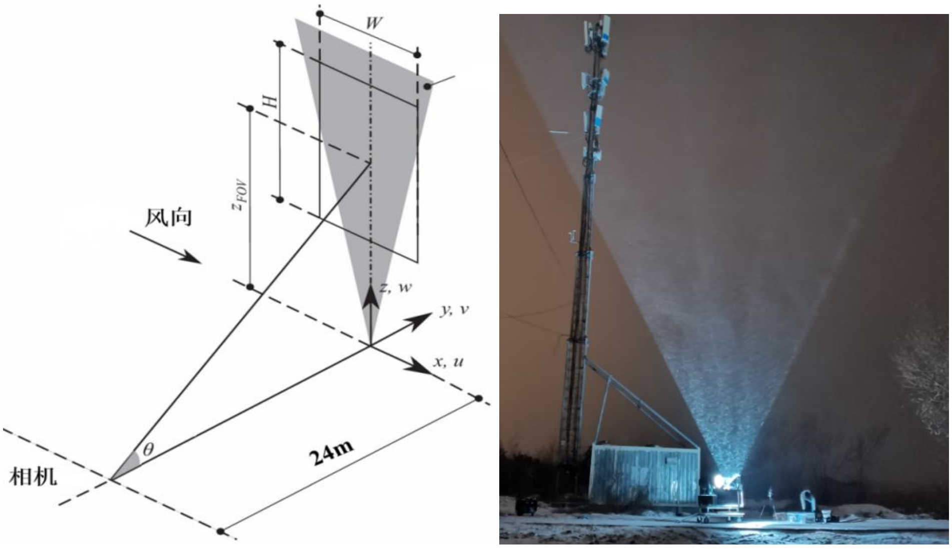


Figure 2-3: Schematic diagram of measurement settings used in experimental deployment (left) and actual field situation (right)

2.2 **Flow Field Reconstruction Method**

This research proposes a composite flow field reconstruction method, which mainly includes the following steps: first, image enhancement is performed on the large-scale PIV video data, including perspective correction, background noise removal, contrast enhancement, and other processing; second, either a cross-correlation-optical flow hybrid method or a particle tracking method is selected to extract flow field information based on the image situation. The noise in this experiment mainly comes from the uneven light intensity of the imaging plane, which is caused by the dense snow particles absorbing the light intensity as the light passes through. The length of snowflakes along the height direction of the light sheet changes due to the camera tilt, and correction is needed to achieve more accurate particle velocity calculation in subsequent processing such as cross-correlation. This research found that image enhancement of snowflake particle images can be effectively achieved using methods such as viewpoint correction, average background subtraction, adaptive histogram equalization with limited contrast enhancement, and adaptive Gaussian thresholding, which can effectively remove noise interference and enhance particle signal strength. The effect is shown in Figure 2-4.

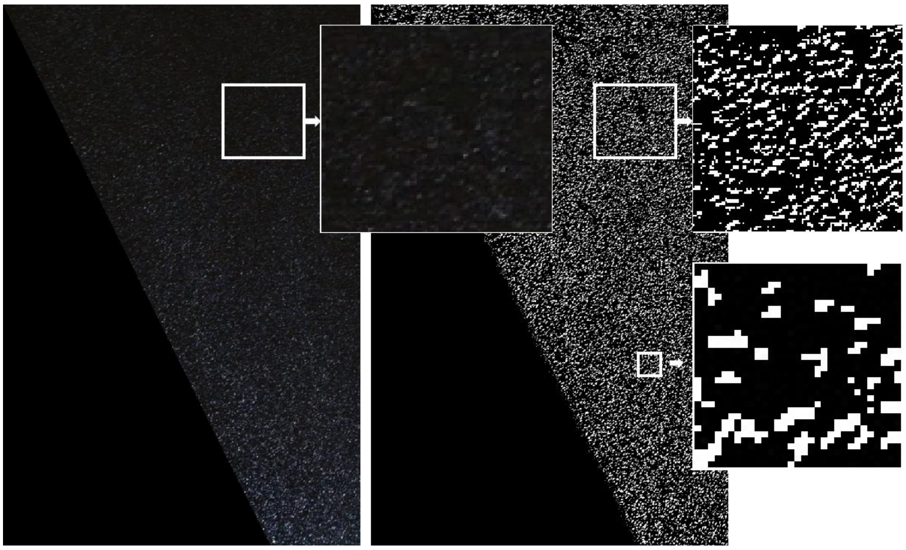


Figure 2-4: Processing Effect of Snowflake Particle Images (Minimum Window Size of 32x32 pixels)

For the large-scale PIV measurement studied in this project, when the particle density is high, a hybrid method that combines the improved cross-correlation method with the optical flow method is proposed for flow field extraction; when the particle density is low, particle tracking technology (PTV) is used to track particles in the sparse particle image sequence.

(1) Cross-correlation/optical flow hybrid method

The principle of the cross-correlation/optical flow hybrid method is shown in the block diagram in Figure 2-5. Because the cross-correlation method is insensitive to displacement size, random noise, and illumination changes in PIV images, starting from a pair of consecutive snowflake particle PIV images (Image A and Image B), the rough displacement field is estimated using the cross-correlation method, and then the shifted image A* is generated based on the rough displacement field. Since the residual displacement amplitude is small at this time, the residual velocity field can be extracted from the shifted image A* and image B using the optical flow method. Finally, the rough displacement field and the residual displacement field are superimposed to obtain the corrected displacement field, and the particle velocity distribution can be obtained through multiple iterations.

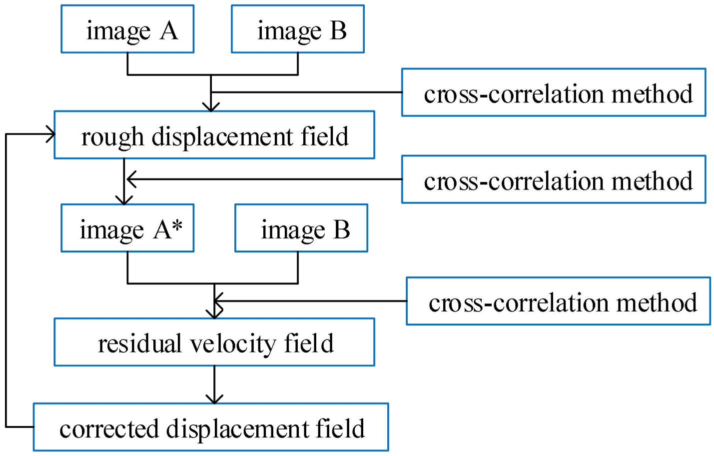


Figure 2-5: schematic diagram of the principle of cross-correlation/optical flow hybrid method.

(2) Particle tracking method

Due to the meteorological environment and uneven distribution of tracer particles or particles being thrown out of vortices due to poor Lagrangian coherence, the local particle concentration in the image may be insufficient. Traditional cross-correlation or hybrid methods cannot be used in such scenarios. To deal with such situations, this research proposes the use of particle tracking velocimetry (PTV) to track sparse particle image sequences and describe the flow field using particle motion information to the greatest extent possible. The particle tracking processing scheme, as shown in Figure 2-6, is applied to solve the problem of sparse tracer particles in large-scale particle image measurements. It mainly includes particle identification, initial trajectory tracking, outlier detection, and trajectory extrapolation modules.

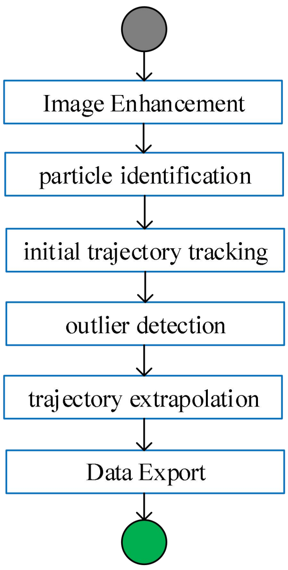


Figure 2-6: Particle Tracking Flowchart

2.3 **Large-scale measurement**

A correction model for the drag coefficient of snow particles was predicted and established using numerical simulation methods. By numerically solving the snow correction equation, the velocity distribution of the background flow field was obtained, and velocity correction was completed.

2.3.1 **Simulation of Snow Drag Coefficient**

Considering the diversity and complexity of snowflake shapes, it is difficult to estimate or fit the drag coefficient of snow particles using empirical formulas. In this research, a relatively standard snow phase-field model was selected as the simulation object, assuming that the maximum projection area of the snowflake is parallel to the incoming flow direction, and the particle Reynolds number matches the measurement results of a hand-held anemometer in large-scale field experiments. The relationship between the drag of snow particles and the particle Reynolds number was obtained, and the drag equation of snow particles was corrected based on the drag relationship equation for standard spherical particles, resulting in the following equation:

$$C_D = \frac{24}{\mathrm{Re}_p}(1 + 0.15\,\mathrm{Re}_p{}^{0.687})\Phi^{-0.2} \tag{2}$$

Where Φ is the sphericity, defined as the ratio of the surface area of a sphere with the same volume as the object to the surface area of the object. Figure 2-7 compares the difference between the drag correction formula and the simulation value at a specified Reynolds number. It can be seen that the correction formula can predict the drag coefficient of snowflakes well within the range of natural particle Reynolds numbers, providing support for the subsequent correction steps.

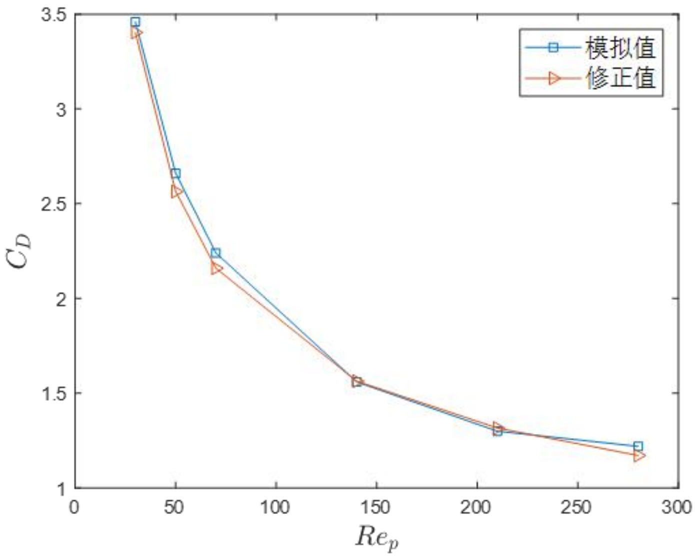


Figure 2-7: Relationship between the drag coefficient of snowflakes and the particle Reynolds number fitted by numerical simulation and correction formula.

2.3.2 **Background flow field acquisition**

Based on the established correction equation and the physical and flow parameters of snow particles, we solve the correction equation by using the velocity extracted from the particle image as the equation input, obtain the velocity of the fluid (air) carrying the particle at the particle position, and use the force on the particle as a bridge between the background flow field and the particle motion. Thus, we obtain the background flow field information of our measurement area, which completes the correction of the snow particle's flow behavior. The correction effect is shown in Figure 2-8.

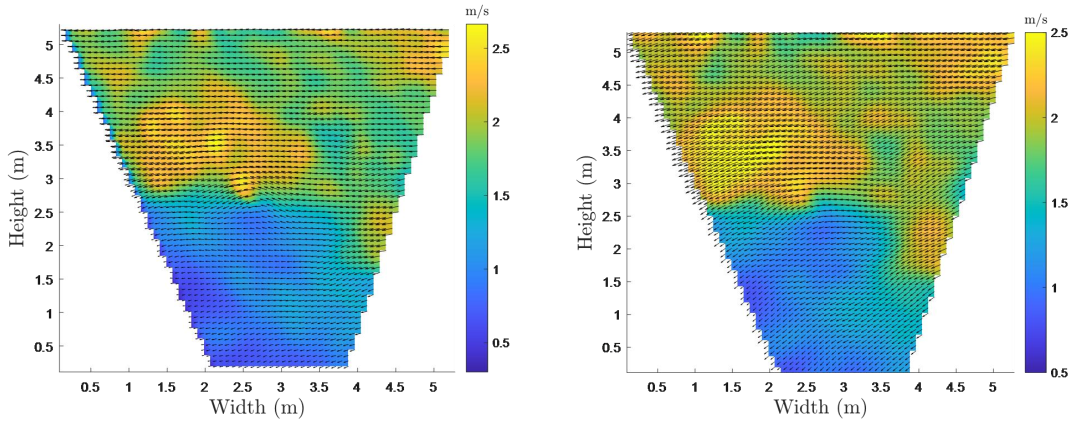


Figure 2-8: Comparison between the corrected large-scale measurement flow field (left) and the original flow field (right)

The comparison between the large-scale corrected flow field and the original flow field (Figure 2-8) shows that, overall, the corrected flow field better reflects the true flow situation. For example, near the spatial coordinates (2.5m, 3.5m) (actual height above ground is about 5.5m), the flow velocity is basically horizontal. The correction algorithm eliminates the velocity brought by the natural downward motion due to gravity of particles at that location, and the overall vertical component of the flow velocity is smaller than the uncorrected value at that location.

2.3.3 **Turbulent flow measurement capability**

In order to further analyze the measurement capabilities of large-scale flow field measurement techniques based on snow particles for turbulent flow, this research conducted a spectral analysis of the atmospheric turbulent boundary layer. The turbulent spectrum is the distribution function of fluid kinetic energy in wave number (wave number) κ space, which can be obtained by integrating the spectrum in κ space.

$$E(\kappa)=\oint\frac{1}{2}\Phi_{ii}(\kappa)\mathrm{d}S(\kappa) \tag{3}$$

The equivalent expression after applying the Dirac delta function is:

$$E(\kappa)=\iint_{-\infty}^{\infty}\frac{1}{2}\Phi_{ii}(\kappa)\delta(|\kappa|-\kappa)\mathrm{d}\kappa \tag{4}$$

The velocity spectrum is generated by the Fourier transform of its correlation function:

$$\Phi_{ij}(\kappa)=F\left\{R_{ij}(\mathbf{r})\right\} \tag{5}$$

The correlation function of velocity is:

$$R_{ij}(\mathbf{r})=\left\langle u_i(\mathbf{x})u_j(\mathbf{x}+\mathbf{r})\right\rangle \tag{6}$$

Where <.> represents spatial averaging, the final velocity spectrum can be expressed as:

$$\Phi_{ij}(\kappa)=F\left\{R_{ij}(\mathbf{r})\right\}=F^{*}\left\{u_i(\mathbf{r})\right\}F\left\{u_j(\mathbf{r})\right\}=u_i^{*}(\kappa)u_j(\kappa) \tag{7}$$

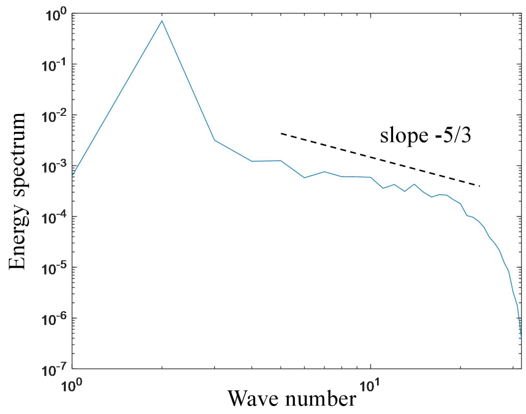


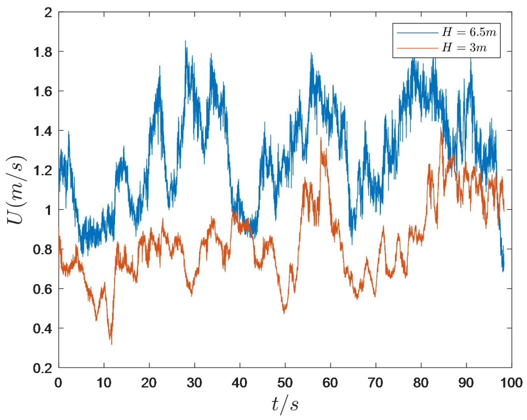
Figure 2-9: Atmospheric turbulence energy spectrum obtained from large-scale measurements

The image recording results at different particle densities are shown in Figure 2-9, with a width and height of 3.36 m and 1.89 m, respectively. Based on the above calculation process, we obtained the turbulence energy spectrum distribution for this measurement, as shown in Figure 2-9(a). The classic -5/3 slope proves that there is an inertial subrange in the measurement results. The turbulent energy is injected from large scales, and the turbulent energy flows along the -5/3 slope from large scales (small κ) to small scales (large κ). Larger eddies are broken down into smaller eddies, and smaller eddies are broken down into even smaller vortices. Finally, the kinetic energy of the fluid is dissipated at a very small scale and converted into internal energy, as shown in Figure 2-9(b). This further demonstrates the ability of large-scale measurement techniques to measure turbulence in the atmospheric boundary layer.

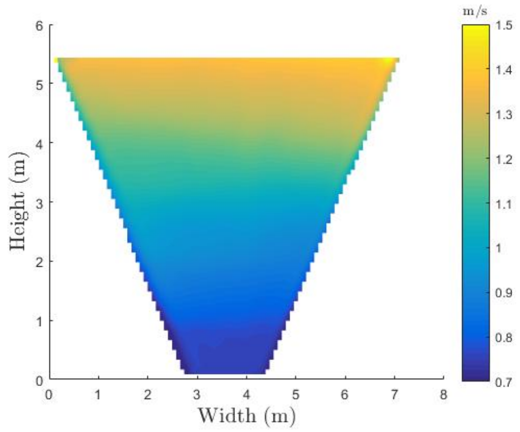
2.3.4 **Near-surface atmospheric flow measurement**

In this research, we measured the near-surface atmospheric flow and obtained the flow structure information with a temporal resolution of 60 Hz and a spatial resolution of 0.08 m. Turbulent fluctuations, mean flow fields, and wind profiles were investigated.

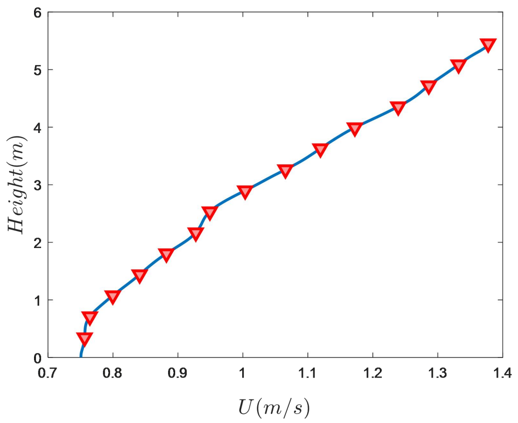
Figure 2-12(a) shows the wind speed fluctuations at heights of 6.5 m and 3 m above ground level, monitored continuously for 100 s. It can be observed that the average wind speed at 6.5 m is greater than that at 3 m, and the relative fluctuation values are slightly larger. Based on the fluctuation data, the turbulence intensities at heights of 6.5 m and 3 m were calculated to be 9.2% and 8.8%, respectively. Since the large-scale PIV measurement described in this paper is a two-dimensional measurement, it can monitor the fluctuations over the entire measurement surface in actual measurement, and can serve as a good measurement method for researching near-surface turbulence. In addition, we processed the atmospheric flow velocity continuously monitored for 100 s and obtained the flow velocity cloud map and wind profile as shown in Figure 2-12(b) and 2-12(c), respectively. From Figure 2-12(d), it can be seen that for small inertial particles in the atmospheric boundary layer, their settling velocities decrease as the height above ground level decreases. This can be explained by the distribution of turbulence dissipation rate, where the gradient caused by turbulent fluctuations plays a positive role in the settling of snowflake particles, and the stronger the turbulence dissipation rate, the stronger the settling enhancement.



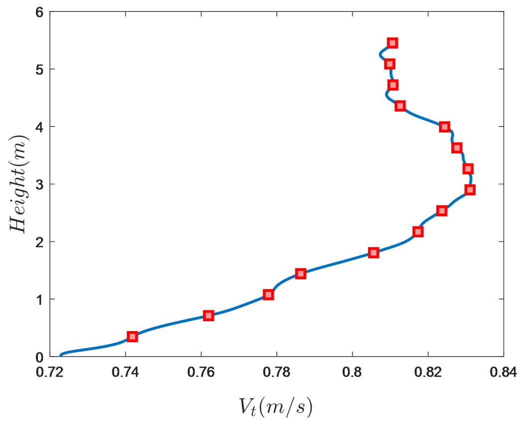
(a) Atmospheric turbulence fluctuations at different heights



(b) Near-surface atmospheric time-averaged flow field



(c) Horizontal velocity profile near the ground



(d) Settling velocity profile of small inertial particles

Figure 2-10: Dependency relationship between system performance and semiconductor film thickness at different system spacings.

3. Research Result

This research designed and built a large-scale particle image velocimetry (PIV) experimental system, which ensured its workability in complex meteorological environments in the field and ensured the smooth progress of large-scale experiments. A whole set of large-scale PIV experimental schemes were established.

This research established a framework for reconstructing the measurement flow field on a large scale, which can effectively process the particle image data obtained from experiments. The image pre-processing scheme can effectively handle distortions and noise in large-scale measurement images and enhance images. In terms of particle flow field reconstruction, this research proposed a hybrid method that combines cross-correlation and optical flow to process large-scale image processing, fully utilizing the advantages of cross-correlation and optical flow. For sparsely distributed particle images, especially locally sparse images generated by uneven scattering in large-scale experiments, a particle tracking framework was used to extract information about individual particles.

4. Published Paper etc.
[Underline the representative researcher and collaborate researchers]
[Published papers]

1. Wang, L.; Liu, J.; Jiang, C.; Li, B.; Song, D.; Lu, M.; Xuan, Y. Large-Eddy Simulations on the Effects of Two Wind Passage Types between Buildings on the Airflow and Drag Characteristics. Atmosphere 2021, 12, 1646. https://doi.org/10.3390/atmos12121646

5. Research Group
1. Representative Researcher
   LI Biao
2. Collaborate Researchers
1. MAO Shengli
2. SU Wenchao
3. JIANG Cunyan
4. XUAN Yingli

6. Abstract (half page)

Research Theme:
Research on large-scale two-dimensional flow field measurement method via natural snowfall trace
Representative Researcher (Affiliation)

LI Biao*, MAO Shengli, SU Wenchao, JIANG Cunyan (Harbin Institute of Technology)
XUAN Yinli (Tokyo Polytechnic Unversity)

This research relied on natural snowfall to provide persistent and environmentally harmless tracer particles and designed a special large-scale experimental system to break through the limitations of particle image velocimetry measurement scales. For the flow field reconstruction method, we established a composite image enhancement framework to correct image distortion and enhance particle signal intensity. We proposed a hybrid method of cross-correlation and optical flow for "dense-type" large-scale particle tracing data and used particle tracking fundamentals to process "sparse-type" data flow. We used numerical simulation methods to predict and establish a correction model for the drag coefficient of snow particles, and based on the relationship between particle and fluid interaction forces, obtained a corrected flow field that better reflects the real flow situation. Finally, the issue of snow particle entrainment was comprehensively discussed, and high-resolution measurements were made of the near-surface atmosphere. The research results showed that snow particles as tracer particles have good effects in large-scale particle image velocimetry.