Wind Engineering Joint Usage/Research Center
FY2023 Research Result Report

Research Field: Outdoor Environment
Research Year: FY2023
Research Number: 23232012
Research Theme: Experimental comparison of 2D flow field around a cube between real scale and model scale

Representative Researcher:

Budget [FY2023]: 360,000JPY

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1. Research Aim

In engineering practice, bluff body forms are widely used in traffic, architecture, aerospace and other fields, such as air resistance analysis caused by airflow around vehicles, wind load design of buildings, etc. The cube is a classical model in the study of the flow around a bluff body, including turbulent phenomena such as impact, separation, reattachment, encircling and vortex. However, current laboratory wind tunnel studies and numerical simulation calculations are severely limited by the inability to reproduce the complexity of real atmospheric flow conditions and the inherent limited spatial scale range resulting in large differences in Reynolds numbers.

In this paper, snowflake particles are used as the tracer particles of large-size particle image velocity measurement to carry out field measurement under the real atmospheric boundary layer, and compare with the experimental results of cube wind tunnels under different scales, so as to deeply study the difference of two-dimensional flow field between full-scale and scale-scale cubic flow around the cube.

- Field measurement of large-scale cubes in a natural wind tunnel

Using the natural frozen river in winter as a natural wind tunnel with uniform and stable incoming flow, field measurement of 2m cube under the real atmospheric boundary layer was carried out. The regularities of wind speed and direction at the measurement site are observed by micro-weather stations, which can provide reference for the experimental arrangement of the scaled wind tunnel.

- Wind tunnel experiments at different scale ratios

The wind tunnel is arranged to restore the incoming flow conditions of the large-scale cube measurement, and the flow around the cube with three different wind speeds and four different scale ratios is measured. The influence of Reynolds effect and scaling effect on the flow around the cube is investigated.

- Comparison between cubic large-scale reconstructed flow field and scaled flow field

According to the classical analysis method of the flow around the cube, the longitudinal velocity at different positions of the cube is compared and analyzed. The attachment length at the top of the cube, the recirculation length at the tail, and the distribution of turbulent kinetic energy were compared.

The large-scale two-dimensional flow field measurement method used in this study can reveal more detailed basic physical phenomena of cube flow, which is of great significance for the design and optimization of more efficient, safe and stable structures and devices. The results can provide reference for rational arrangement of wind tunnel experiment and evaluation and correction of numerical simulation calculation.

2. Research Method

2.1. Full-scale natural wind tunnel

Many scholars have carried out full-size or large-size field measurement tests in natural wind tunnels. Richards et al. [1-3] from Silsoe Research Institute in New Zealand built a 6 m cube in an open outdoor position, as shown in Figure 2-1(a), and made detailed measurements of the surface pressure of the cube and the wind speed in the surrounding area. The research of Levitan and Richards et al. provides effective field measurement data for wind tunnel scaling experiments and numerical calculation of turbulence models, but the numerical research data are only one-dimensional measurements of single-point flow field based on pressure sensors. In order to display the two-dimensional flow field pattern around the 24×13×4 m frame building, Hoxey and Richards[4] made tracer observations by fixing the smoke generator around the building, as shown in the right picture in Figure 2-1(b). In order to overcome the limitations of existing wind tunnel test methods for bridge wind engineering research, Professor Xu Fuyou's team [5] from Dalian University of Technology of China proposed a new experimental method, that is, based on large-scale bridge floor section model and full bridge aeroelastic model, as shown in Figure 2-1(c), to study the wind resistance performance of Bridges under natural wind conditions and provide representative wind field data. The feasibility of this experimental method is briefly verified. The study points out that wind field data is the most important concern of this experimental method. It is normal that the wind profile, spectrum, integral length and spatial coherence of natural wind can not meet the experimental requirements well. Some measures can be taken to adjust the wind field to make it closer to the target. For example, wind speed and turbulence intensity can be reduced by using windbreak nets. Meshes and small helical structures can increase turbulence intensity and regulate wind profiles, spectra and coherence.

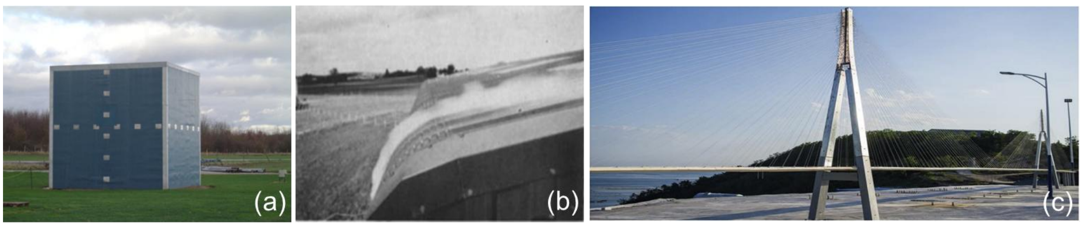

Figure 2-1 6 m cube in natural wind tunnel (a), building flow field measurement (b) and large-scale bridge measurement (c)

Large-scale wind tunnels cannot completely simulate the real atmospheric boundary layer flow conditions, so this paper will carry out full-scale field measurement of 2m cube in outdoor environment. Despite the uncontrollability and complexity of the real atmospheric environment, this study took advantage of the geographical advantage of ice on the Songhua River and relatively stable wind direction in Harbin in winter (Figure 2-2 (a)). A location with few surrounding buildings was selected by satellite map, and a tributary of the Songhua River near Binshui Avenue, Songbei District, Harbin, was selected as the test site, with the length of both sides of the river reaching about 336 meters, as shown in Figure 2-2 (b). The area is open and flat, and there are no large hills or buildings around it. In winter, the southwest wind dominates the direction of this location. The frequency of wind direction was 22.3%, followed by west-southwest wind (frequency 14.5%) and west wind (frequency 10.9%), which could provide uniform and stable incoming flow. During the experiment, information such as snowfall, wind speed and wind volume were obtained by weather forecast, and cubic incoming wind speed was recorded with high-precision split anemometer. The measuring range of wind speed measured by the instrument was 0.3~45 m/s.

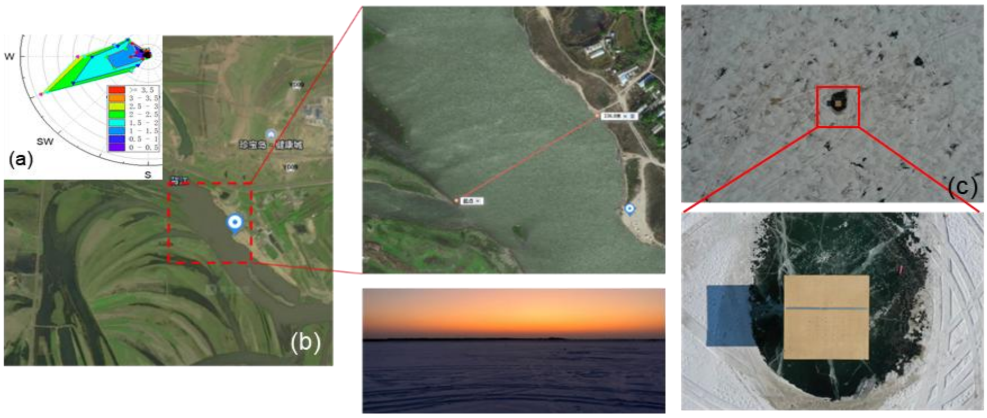

Figure 2-2 Wind speed and direction distribution (a), natural wind tunnel (b) and cube shooting (c)

2.2. Full scale field PIV measurement by snowflake tracer

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 [6]. With high spatiotemporal resolution, PIV is the only experimental method that can provide instantaneous fluid vorticity and strain rate information in rapidly changing fluids [7]. Hong et al. [8] 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. [8], 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 [9]. Details of experimental measurement methods can be found in reference [9]. Using this large-scale flow field measurement method, the field measurement of 2m cube in a natural wind tunnel was carried out in this report, as shown in the figure. The light sheet system is located at the tail of the incoming stream cube to display the wake flow field information, as shown in Figure 2-3 (c). The distance between the camera and the film light is 24 m. The experiment used a commercial camera with 12 megapixels. The lens used is 50mm prime lens, shutter speed 1/500s, aperture 1.2, video recording frame rate of 120 frames/SEC, video resolution of 3840×2160. The field of view FOV measured at this scale is 12m×6.75m.

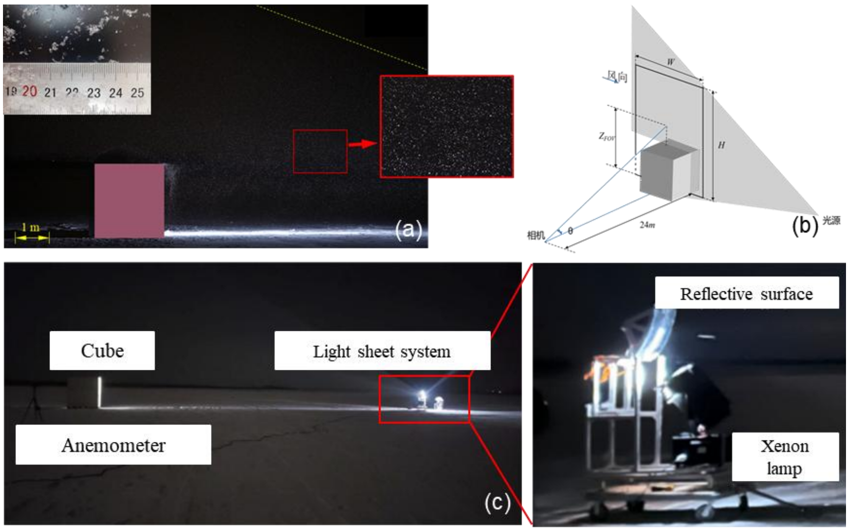

Figure 2-3 Actual shooting of cubes (a,b) and site layout (c)

2.2. Wind tunnel scaling experiments under different Reynolds numbers

2.2.1. Arrangement of wind tunnel experiment

With the help of the temperature stratification wind tunnel of Tokyo Polytechnic University, Japan, the wind tunnel experiment of a 2-m cube was realized at four scales of 1/20, 1/40, 1/100 and 1/200, and three wind speeds of 0.6m/s, 1.2m/s were set for flow. The temperature stratification wind tunnel is composed of blower, diffusion cylinder, rectifier, shrinkage cylinder, measuring cylinder, temperature stratification device, floor heating and cooling plate and return flow cooling device. The blower is a 5.5kW DC double-suction fan with a minimum wind speed of 0.5m/s and a measurement section size of 1.2 ×9.37×1.0 m, as shown in the left figure of Figure 2-4.

Figure 2-4 Temperature Stratification wind tunnel (left) and cube scale model (right)

The tracer particles in the wind tunnel experiment were olive oil droplets (with a particle size distribution of 1-5 μm), which were generated by an oil droplet atomizer produced by FLOW RESEARCH in Japan, as shown in the left picture of Figure 2-5. Figure 2-5 The right picture shows a wind tunnel measurement of a 1/100 scale model. The images were captured using the FASTCAM Nova S12 high-speed camera, which has a maximum resolution of 1024×1024 and a maximum shooting speed of 12,800 frames per second.

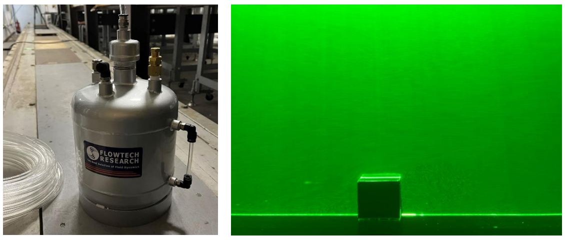

Figure 2-5 Oil drop generator (left) and 1/100 wind tunnel measurement (right)

2.2.2. Wind tunnel incoming flow construction

In order to provide reference for the reconstruction and correction of the natural wind tunnel external field experiment, the wind tunnel scale experiment needs to restore the atmospheric near-surface wind field during the external field experiment. The curve describing the change of the average wind speed in the atmospheric boundary layer with the altitude above the ground is called the Mean WindSpeed Profile or mean windspeed profile. The average wind velocity profile is generally described by logarithmic or exponential law [10] :

$$U(z)=U_r(z/z_r)^{\alpha} \tag{2-1}$$

Or

$$U(z)=U(z_G)(z/z_G)^{\alpha} \tag{2-2}$$

In the formula：

U_r is the wind speed at the reference height z_r above the ground;

α is the ground roughness index, and its value is related to the type of ground roughness;

$U(z_G)$ is the average wind speed at the gradient wind height z_G.

With different roughness categories, the α value is not the same, and the height of the gradient wind speed is not the same, that is, the average wind speed profile is also different. China's "Building Structure Load Code" GB50009-2012 divides ground roughness into four categories, and the various types of ground roughness and their corresponding α and zG values are shown in Table 2-1.

Table 2-1 Chinese standard ground roughness category and corresponding α and z_G values

Surface roughness type	Description	α	z_G
A	Offshore sea, islands, coasts and desert areas	0.12	300
B	Fields, villages, jungles, hills, small towns with sparse houses and suburbs of large cities	0.15	350
C	An urban area with a dense cluster of buildings	0.22	450
D	A large urban area with dense buildings and a large number of tall buildings	0.30	550

The natural wind tunnel experiment of this subject belongs to the type B ground roughness in the above table. In the wind tunnel experiment, right-angle steel bars were used to increase the roughness of the wind tunnel ground, as shown in Figure 2-6(a). The right figure in Figure 2-6(b),(c) shows the reconstructed wind profile of 0.6m/s, 1.2m/s and 2m/s wind speeds, and the calculated ground roughness index is about 0.25, 0.25 and 0.17, respectively. It can be seen from the turbulence intensity diagram that the turbulence intensity of 0.6m/s and 1.2m/s incoming flow is basically the same, and the turbulence intensity of 2m/s incoming flow is higher than the previous two wind speeds.

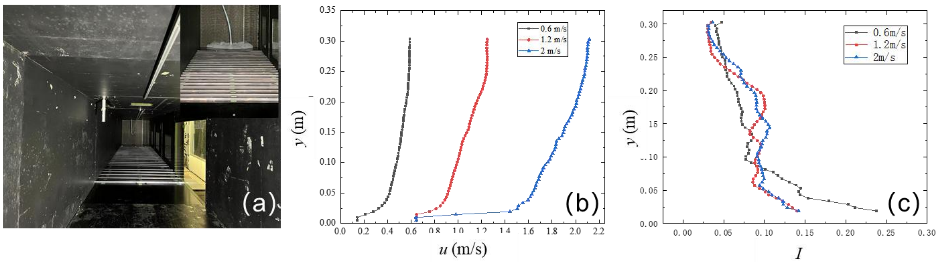

Figure 2-6 Roughness layout of wind tunnel (a) Average wind velocity profile (b) and turbulence intensity (c)

3. Research Result

3.1. Large-scale cube reconstruction of flow field and gravity correction

The image pre-processing process is based on imageJ software. The basic process is background subtraction → brightness enhancement → median filtering. In PIVlab software, an adaptive multi-channel algorithm is used to carry out cross-correlation operation, and the reconstructed flow field of a large scale cube is obtained. The initial query window size was 128×128 pixels, and subsequent optimization produced a final window size of 64×64 pixels with an overlap rate of 50%, resulting in a PIV flow field resolution of 0.2m. The particle displacement in the query window is 5pixel, which is less than 1/4 of the query window size, meeting the cross-correlation operation requirements. Figure 3-1 shows the time-mean flow field without gravity correction. It can be seen that the overall flow line shows a downward trend under the influence of snowflake particles. The vortex at the end of the cube is not obvious and cannot reflect the real flow field. Figure 3-2 shows that the Y-direction component of snowflake velocity vector is corrected to remove the snowflake sedimentation caused by gravity in the air flow field.

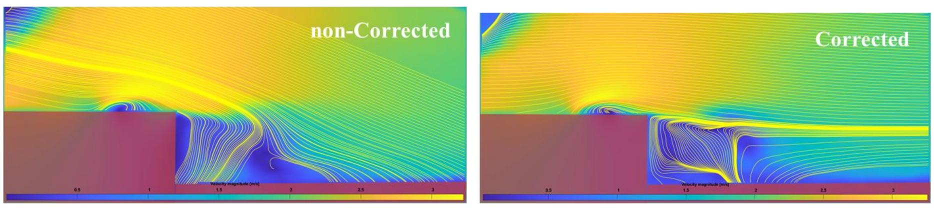

Figure 3-1 Comparison of time-averaged flow field in a large-scale cube

Because the cube blocks the light, the flow field in front of it is not shown. From the modified time-mean flow field, it can be seen that there are obvious shear layer and reattachment area at the top of the cube. The flow field structure of the cube tail is quite different from that of other researchers, which is caused by the poor fluidity of snowflake particles themselves. The tail recirculation length of the cube is about 1.1D.

3.2. Flow field reconstruction and analysis in wind tunnel

The wind tunnel flow field is reconstructed in the same way as the large-scale cube, with an initial query window size of 64×64 pixels, and subsequent optimization produces a final window size of 32×32 pixels with an overlap rate of 50%. Figure 3-2 shows the instantaneous flow field and time-mean flow field of 1/20 cube (10cm) at Re=4060. From the instantaneous flow field under this Reynolds number, it can be seen that there is a vortex core in the front of the cube, reattachment and vortex shedding at the top of the cube, and secondary vortices are generated at the tail of the cube. The instantaneous flow state at the end of the cube indicates the inherent three-dimensional character of the flow. It can be seen from the time-mean flow field that the height of the separation area at the front of the cube is about 0.5D, the adhesion at the top of the cube is about 0.8D, and the recirculation length at the tail of the cube is about 1.4D. The result is similar to that obtained by Yakhot et al. [11] at Re=5610 by DNS and 1.5D.

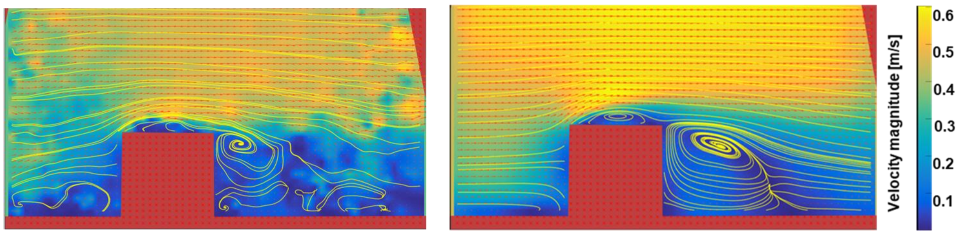

Figure 3-2 Instantaneous flow field and time-mean flow field of 1/20 cube

3.3. Comparison of large-scale flow field with wind tunnel scale

Figure 3-3 shows comparison of longitudinal flow fields at different locations under different Reynolds numbers. It can be seen from the figure that cube models of different proportions with different Reynolds numbers have similar basic flow structure under the condition of turbulent boundary layer inflow, but the vertical velocity change rate of the full-scale cube in different places along the flow direction is higher than that of the scaled model. In addition, models of different proportions appear to have different critical values of Re independence, which increase as the scale ratio of the model decreases. This result is different from the critical value Re=11000 of conservative Reynolds number independence proposed by Snyder for a similar cube model [12]. This is the same as Uehara's conclusion that Reynolds number is not unique for different situations by studying critical Reynolds number through a series of wind tunnel experiments under different Reynolds numbers [13]. Shu refers to the fact that there seems to be no unique critical Reynolds number for general case [14].

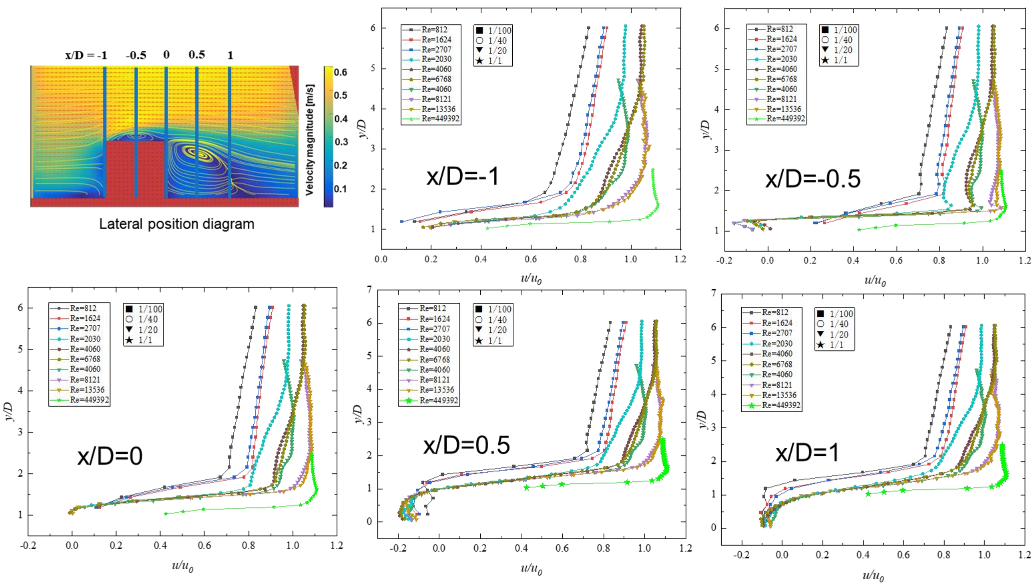

Figure 3-3 Comparison of longitudinal flow fields at different locations

under different Reynolds numbers

Figure. 3-4 shows the comparison of the top and tail flow fields under different Reynolds numbers. As can be seen from the figure, there is no reattachment point on the top of the cube at low Reynolds number, and the top reattachment point appears with the increase of Reynolds number, and the reattachment position gradually decreases, but there is no reattachment point in the full-scale model at high Reynolds number. The reason for this phenomenon is that snowflakes with poor fluidity are used as tracer particles, which cannot enter the top vortex, so that the reattachment point on the top of the full-scale cube cannot be captured. The recirculation length of the tail of the cube appears at all Reynolds numbers. With the increase of Reynolds number, the recirculation length first increases and then decreases, and finally stabilizes at 0.9D position. This conclusion is in line with the results obtained by Khan's research around a cube wind tunnel of 500~55000, which shows that the recirculation length of the cube increases at Re=785, and then decreases at higher Re, finally showing Reynolds independence [15]. The recirculation length shows Reynolds independence, and the Reynolds independence of the vertical velocity along the flow to different places is also related to the scale of the model.

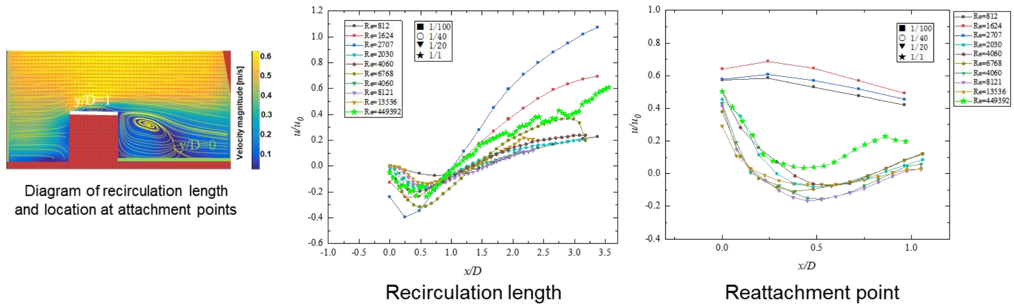

Figure 3-4 Comparison of top and tail flow fields under different Reynolds numbers

Figure. 3-5 shows the comparison of dimensionless turbulent energy between a large-scale cube and a 1/20 scale cube. It can be seen from the figure that the non-dimensional turbulent kinetic energy distribution of the full-scale cube is similar to that of the wind tunnel model, but the maximum turbulent kinetic energy of the full-scale cube is higher than that of the wind tunnel scale experiment, and both appear at the upper front of the cube incoming flow. This conclusion is in accordance with Hoxey's conclusion that the pressure value at the roof of the full-scale cube of Silsoe 6m is lower than that of the wind tunnel experiment when compared with the scaled wind tunnel model [1].

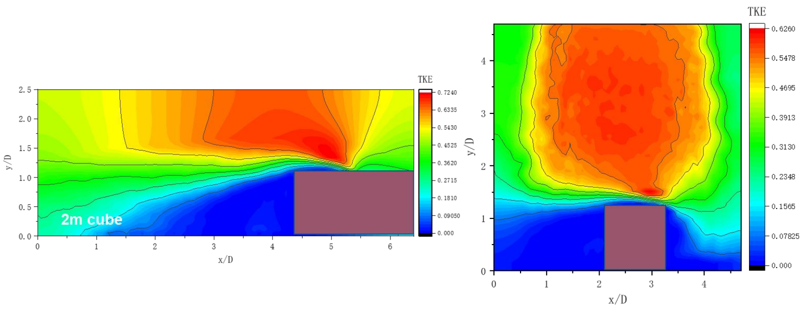

Figure 3-5 Comparison of dimensionless turbulent energy between a large-scale cube and a 1/20 scale cube

4. References

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Research Theme
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Summary・Figures

In this paper, snowflake particles are used as the tracer particles of large-scale particle image velocimetry (PIV) to measure the flow field under the real atmospheric boundary layer of 2m cube in an open frozen river with stable incoming flow. The difference of two-dimensional flow field between full scale and scale scale is studied by comparing with the wind tunnel scaling experiments under four different scales and three different wind speeds. The results show that the cubic models with different proportions and different Reynolds numbers have similar basic flow structure under the condition of turbulent boundary layer inflow, but the vertical velocity change rate of the full-scale cube is higher than that of the scaled model. At low Reynolds number, there is no reattachment point on the top of the cube, and with the increase of Reynolds number, the top reattachment point appears, and the reattachment position gradually decreases. At high Reynolds number, the reattachment point of the full-scale model does not appear. The reason for this phenomenon is that snowflakes with poor fluidity are used as tracer particles, which cannot enter the top vortex, so that the reattachment point at the top of the full-scale cube cannot be captured. The non-dimensional turbulent kinetic energy distribution of the full-scale cube is similar to that of the wind tunnel model, but the maximum turbulent kinetic energy of the full-scale cube is higher than that of the wind tunnel experiment, and both appear at the upper front of the cube incoming flow.