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# A stereo PIV measurement of a model ship wake in a towing tank with uncertainty assessment

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**ABSTRACT**

Detailed information of the flow around a ship is essential for designing the hull because it is related to the propeller performance, maneuverability, and vibration. Thus, lots of experimental and computational researches have been executed to measure or analyze the stern flow of vessels. In this paper, the newly installed underwater SPIV system in Seoul National University Towing Tank is introduced with its measurement results and estimated uncertainty.

The SPIV system was installed on the towing carriage which runs along side rails of the towing tank. With the underwater SPIV system, the uniform flow, made by running the towing carriage without a model, was firstly measured to investigate the uncertainty assessment. Uniform flow measurement results for each direction of the coordinate system were analyzed to estimate the random error and systematic error, following the ASME test uncertainty. The reference speed for the longitudinal and transverse uniform flow measurement was set to 1.0m/s and 1.5m/s, which is general towing speed range of model ships in the towing tank. In the uniform flow measurement results, the systematic error, the difference of ensemble-averaged speed and reference speed from the encoder of the towing carriage, was below 1.5% of the towing speed and the random error, derived from the standard deviation of the ensemble-averaged speed, was 4% of the reference speed.

After the uncertainty assessment, the nominal wake, the flow on the propeller location with absence of the propeller, was measured and results were compared with experiment results with 5-holes Pitot tube from other towing tank. The model ship was KVLCC2, of which hull design and dimension are open to public. The scale of the model ship was 1/100, and the Froude number was 0.142 in the design speed. SPIV results showed good agreement with existing results and have advantages such as depiction of turbulence properties and reduction of the experiment-operating time.

## INTRODUCTION

In designing a ship hull, hydrodynamic performance and flow characteristics around the hull is very basic and essential part. Thus, some experimental techniques have been introduced to naval architecture to measure the flow field around hulls, especially their stern, the rear side of a ship. For experiments for hydrodynamic research of a ship in model scale, a towing tank is currently used since it can provide uniform flow, simulated sea waves, and ignorable blockage effect with a model ship in relatively larger scale than other experimental facilities, such as circulating water channels and cavitation tunnels.

Traditionally, Pitot tube is used to measure a flow field in the towing tank as it is easy to install and operate. Results with Pitot tube [1, 2, 3] have been used as a validation data for other experimental or computation results, but as Pitot tube system is not sufficient to access turbulence characteristics, alternative techniques are introduced into towing tanks such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) [4]. Although LDV is very accurate and has high repetition rate, it is point-wise measurement technique and time-consuming. In the towing tank experiment, the operating time of a measurement system is limited to the length of towing tank and the speed of towing carriage. In contrast to LDV, PIV can measure a flow field of a plane and save time, so it is suitable to towing tank experiments. With towing tank PIV systems, various measurements were performed such as flow around surface combatant model in planar motion mechanism (PMM) [5], rotating propeller in open water [6], stern with energy saving device [7], and very large crude carrier (VLCC) model [8].

In the towing tank PIV, optical arrangement of components is quite limited to achieve lower hydrodynamic drag of the housing and the flow direction is usually perpendicular to the measurement plane. In addition, as the principle of the towing tank is to make a uniform flow spatially and temporally, a unique calibration procedure using uniform flow measurement was suggested [9]. These characteristics make PIV in towing tank different from other PIV systems and an uncertainty assessment for towing tank PIVs is required currently. As the data reduction equation for PIV is quite complex, the uncertainty assessment for towing tank PIV is based on the compare with other references such as Pitot tube results and the speed from the rotating encoder of the towing carriage [5].

In this study, the newly-installed towing tank SPIV in Seoul national university is introduced and its uncertainty is estimated with uniform flow measurement results. After the uncertainty assessment, a nominal wake, a flow field at propeller plane with absence of propeller is measured and compared with existing experimental results. Lastly, turbulence characteristics of the nominal wake field are analyzed.

## TEST FACILITY AND MODEL

The SPIV measurement was executed in Seoul national university towing tank. Length, depth, and width of the towing tank are 110m, 3.5m, and 8m, respectively. On the towing tank, a towing carriage driven by four servo motors runs along rails and its maximum speed is 5m/s. The speed in controlled with 0.2% of accuracy with closed feedback controller. In the experiment, the SPIV system and model ship is attached on the towing carriage, and runs with constant speed. Fig. 1 is the design of the towing tank and towing carriage, and Fig. 2 is the design of SPIV system. In the towing tank, the right-handed coordinate system is used: positive x for forward direction, positive y for starboard direction, and positive z for upward direction. The traverse system for the SPIV contains a turntable and whole SPIV system can be rotated on z-axis, thus the measurement plane also rotates from yz plane to xz plane. Fig. 3 is the picture of the SPIV system with a model ship.

The SPIV system is made by LaVision from Germany. It contains dual head Nd:YAG laser with 200mJ pulse power, two five-mega pixels cameras with 12bit of dynamic range. Repetition rate of the camera system is about 7.5Hz, and with camera lens with 50mm of focal length, the size of field of view is 110mm * 110mm. The laser sheet optic, camera and lens are placed in vertical circular cylinders, and the focus, aperture, and scheimpflug angle controller is positioned between the lens and camera CCD. To meet the scheimpflug condition, CCD module is rotated while the camera lens is fixed. Distance between the laser sheet optic and the center of the field of view is 850mm. The thickness of the laser sheet is 2mm. Fig. 4 is the diagram of optical arrangement of SPIV system. Polyamide particle with 18um of mean diameter is used for tracer particle. For the experiment, tracer particle was mixed in a pre-mix tank, and the mixture of polyamide, water, and soap is sprayed into the towing tank by pressure of compressed air.

For the research, a VLCC hull developed by Korean Research Institute of Ships and Ocean Engineering (KRISO) is used. KRISO VLCC2 (KVLCC2) was designed for research, not commercial purpose. Fig. 5 is the design of KVLCC2 model. The hull, propeller, and rudder design are opened and it has been used for various ship hydrodynamic researches, such as propulsion performance, maneuvering, and seakeeping ability. In this study, scale of the model ship is 1/100. In Table 1, the dimension of full-scale ship and the model ship is described.

Using the towing tank SPIV system, the flow field at the longitudinal position of the propeller was measured. Since the field of view is limited, PIV measurement was repeated in different y and z position. The position of whole measurement plane was from -40mm to +375mm in y-direction and from -100mm to +150mm in z-direction when the origin locates at the center of the propeller. Whole measurement plane was divided into 12 zones. At each zone, 250 particle image pairs are captured during one towing carriage run. For the camera control and data acquisition, Davis V8.0, PIV software from LaVision, was used.

**UNCERTAINTY ASSESSMENT AND UNIFORM FLOW MEASURMENT RESULTS**

To calibrate the SPIV system, a two-leveled calibration plate with grooves was used. The depth of the groove lines is 3mm, and dots are arranged on the plate and in grooves with 15mm of spacing. 3rd polynomial equation was derived from the captured image of calibration plate, and root-mean-square of the difference between the dot position and calibration equation for camera 1 and 2 was 0.013 and 0.021, respectively.

Captured particle image pairs were analyzed by Davis V8.0. Firstly, images from two cameras were dewarped and two-dimensional (2D) velocity vectors were derived by the cross correlation. Size of the interrogation window was 64 pixels * 64 pixels, with 50% of overlap. The cross correlation was applied without iterations or the interrogation window size decreasing. After three-dimensional (3D) velocity vectors were reconstructed by calibration results and 2D vector fields, velocity vectors were validated by its length. The threshold for range validation was 10% of towing speed. Validated vector fields were then ensemble-averaged into one vector field. RMS for each component of the velocity vector was also derived. Averaged velocity and its RMS were divided by towing speed and non-dimensionalized. Turbulence kinetic energy (TKE) is also divided by square of the towing speed.

Firstly, uniform flow cases in 1.0m/s and 1.5m/s were measured at y-z plane, which is perpendicular to towing direction. In the principle of the uncertainty assessment from the American society of mechanical engineers (ASME) [10], the test uncertainty of a measurement system is defined by two components: a systematic error and random error. The systematic error is difference between a reference value and average of measurement results with large numbers of samples, and the random error is the difference between instantaneous value and the average. In the uniform flow measurement, the systematic error can be derived by comparing the ensemble-averaged velocity and the reference speed, x-dimensional speed from the speed encoder of the towing carriage. In addition, the random error is from RMS of the flow field samples. With systematic and random error range, total uncertainty for velocity measured by the SPIV system could be estimated.

The principle of the towing tank experiment is that there is only x-directional speed when the towing carriage runs in the calm water condition. Transverse and vertical speed and turbulence are not expected, so the reference for these components is zero. In the towing tank, the blockage effect of the SPIV system is ignorable and the inflow is considered as spatially uniform as well as temporally. If any kinds of non-uniformity in the systematic and random error distribution are observed in the uniform flow test, its reason can be investigated. For the towing tank SPIV system, sources of the uncertainty are various: the flow affected by cylindrical housing of the PIV, initial turbulence in the towing tank, mechanical vibration, disparity between calibration plate and laser sheet, and discretized brightness data of the particle image.

Fig. 7 is averaged velocity from uniform flow measurement results on y-z plane. Systematic error distributions in different speeds look similar. In capturing particle image, $\Delta t$ between two frames are carefully chosen to make the displacement of particles is under 5 pixels, thus particle displacement in images is independent to the uniform flow speed. As displacement of particles is all constant in the uniform flow, disparity in calibration equation and optical characteristics seem to be the cause of the proper distribution of the systematic error. In addition, the systematic error is also independent to the analyzing procedure because only cross correlation is applied once without comparing to its neighbor. The local maxima of the systematic error for x, y, and z direction are 0.6%, 1.2%, and 0.4%, respectively. It is noteworthy that the systematic error of the out-of-plane component, u/U, is comparable to on-plane components. Besides, z-directional component of ensemble-averaged velocity is the lowest among three components since vertical positions of cameras are same and disparity in z-directional component hardly occurs.

Fig. 8 is RMS from the uniform flow measurement. The local maximum is about 4 % for every component and spatial average is 2.2%, 1.7%, and 1.5% for x, y, and z direction, respectively. The RMS of u/U is also comparable to other components and the RMS of w/U is the lowest. Although the towing test starts after the water surface becomes calm, there is surely residual turbulence in the water, and it is measured in the uniform flow test. Optical characteristic and vibration of the whole experimental system are other factor in the RMS of averaged velocity. In this test, as the RMS distribution is similar in different speed, optical property of SPIV system is considered as the major source of the random error, same with the systematic error. The result of uncertainty assessment of y-z plane measurement is shown in Table 2.

Lastly, uniform flow fields in 1.0m/s and 1.5m/s were measured at x-z plane. To measure the plane, SPIV system is rotated with turntable. Thus, the arrangement of the SPIV system remained unchanged, but the flow direction became to be parallel to the measurement plane. Figs. 9 and 10 are results of averaged velocity and RMS. Like y-z plane cases, proper patterns on systematic and random error distribution are observed and they look alike in different speed. The systematic error of u/U and v/U is slightly larger than the y-z plane cases, but it can be reduced by adjusting the direction of SPIV system with the turntable carefully.

## KVLCC2 WAKE MEASUREMENT RESULTS

Particle images from the KVLCC2 wake measurement are shown in Fig. 11. Since background image from the model ship affects to the cross-correlation, image filter is applied. Other procedure such as cross correlation, range validation, and averaging 250 samples are same with uniform flow cases. Fig. 12 is the whole flow field.

As shown in Fig. 13, non-dimensionalized velocity distribution is compared with 5-holes Pitot tube results in KRISO towing tank [1]. The Pitot tube experimental data were measured at Reynolds number of 5,250,000, which is 2.26 times larger than SPIV test. Since Reynolds number is different, Pitot tube case with higher Reynolds number shows thinner boundary layer. Except the boundary layer thickness, SPIV results and Pitot tube results shows good agreement including hook-shape region and bilge vortex. In addition, SPIV can detect local vorticies just under the propeller center with low speed region while it is not observed in Pitot tube results due to low spatial resolution and limitation in measurable flow direction in Pitot tube system.

Fig. 14 is the TKE distribution. TKE is concentrated at where the gradient of u/U is greater. At the region with high gradient of u/U, TKE is about 3% of the kinetic energy of the free stream. The turbulence is anisotropic, and the portion of the x-directional fluctuation takes more than half of TKE.

## CONCLUSIONS

In this study, newly installed towing tank SPIV system is introduced and its uncertainty is assessed with the uniform flow measurement. The estimated uncertainty range of the y-z plane measurement is 3.42% of towing speed, and it is mainly from the random error. With the uncertainty results, the stern flow of KVLCC2 model ship is measured and compared with 5-holes Pitot tube test results. Considering different Reynolds numbers of two tests, it shows reasonable agreement and in SPIV result, local vorticies and low-speed region is well observed. TKE is also derived as well as averaged velocity. With SPIV in towing tank, it is expected to be applied to researches for flow phenomena that Pitot tube and other measurement system are not able to measure, such as phase-averaged propeller inflow, turbulent characteristic of stern flow, and flow with wave condition.

## ACKNOWLEDGEMENT

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Table 1. Principal dimensions of KVLCC2

| | Full scale | Model |
|---|---|---|
| Scale ratio | 1 | 1/100 |
| Waterline length (m) | 325.5 | 3.255 |
| Beam (m) | 58.0 | 0.58 |
| Draft (m) | 20.8 | 0.208 |
| Wetted surface area ($m^2$) | 27,194 | 2.719 |
| Displacement ($m^3$) | 312,622 | 0.312 |
| Propeller diameter (m) | 9.8 | 0.098 |
| Reynolds number in design speed | $2.14 * 10^9$ | $2.32 * 10^6$ |
| Froude number in design speed | 0.142 | |
| Block coefficient | 0.8098 | |

Table 2. Uncertainty assessment results of y-z plane measurement

| | u/U | v/U | w/U |
|---|---|---|---|
| Systematic uncertainty (%) | 0.6 | 1.2 | 0.4 |
| Random uncertainty (%) | 3.6 | 3.4 | 3 |
| Total uncertainty (%) | 3.65 | 3.61 | 3.03 |

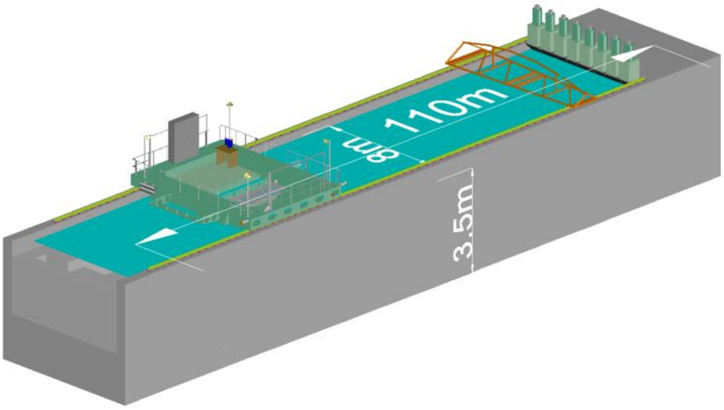


**Figure 1** The design of the towing tank

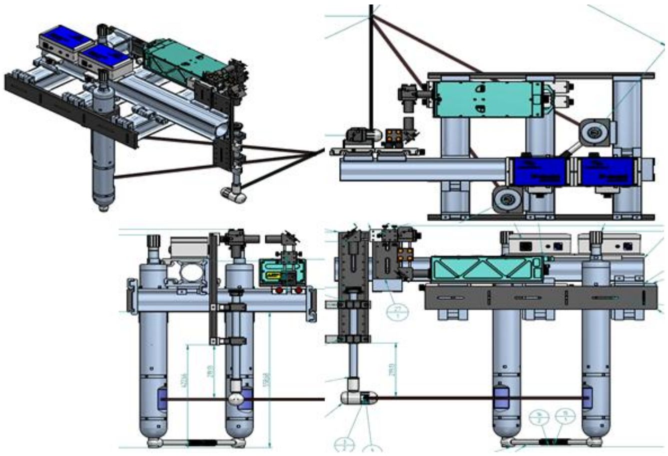

**Figure 2** The design of the underwater SPIV

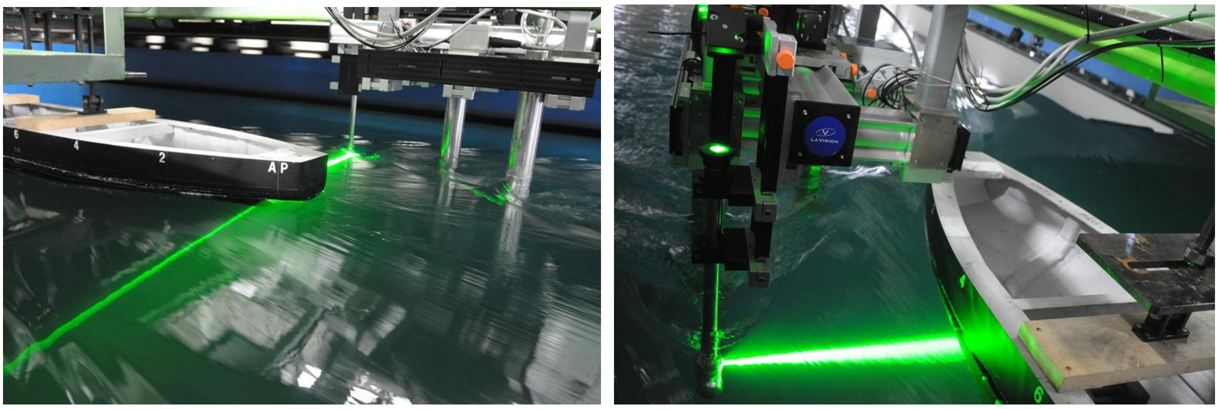

**Figure 3** Snapshots of the experiment

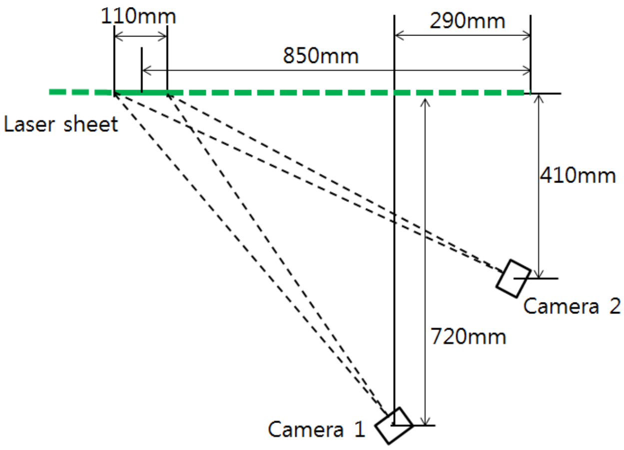


**Figure 4** The diagram of the SPIV arrangement

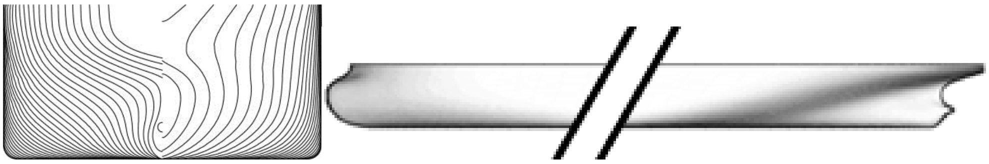

**Figure 5** The body plan and profile of KVLCC2 model ship

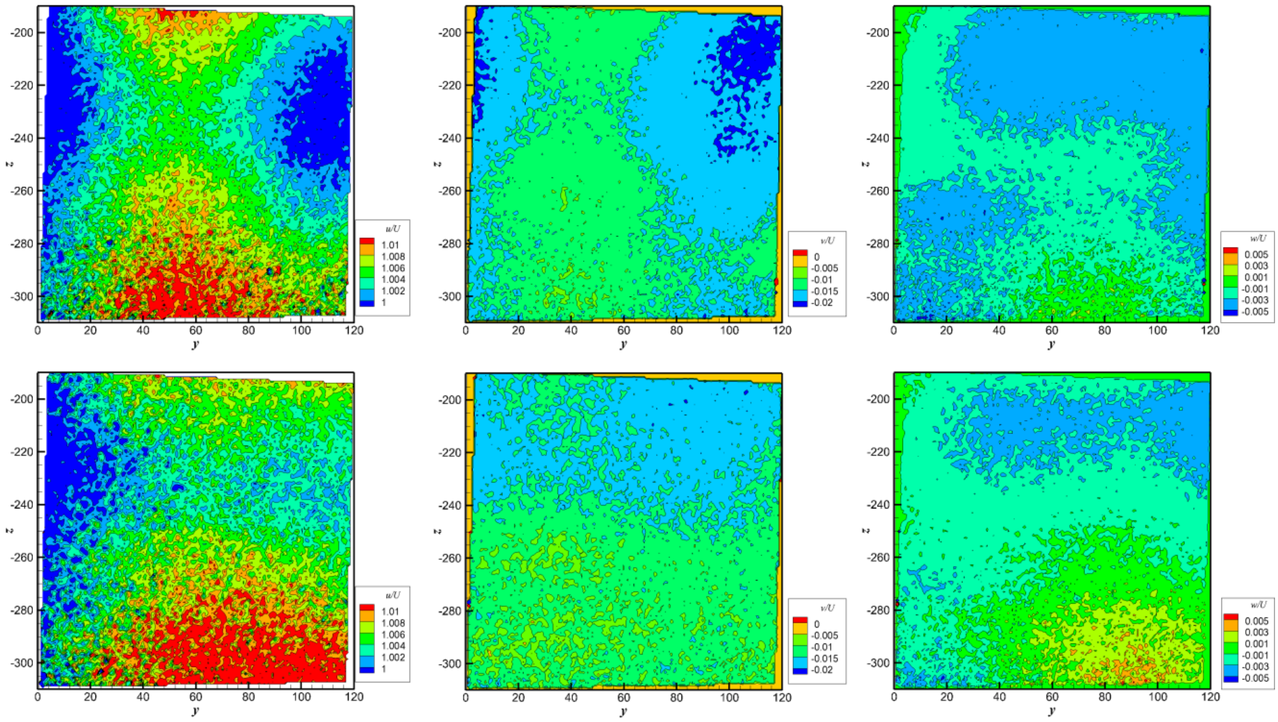

**Figure 6** Velocity distribution for y-z plane (top: 1.0m/s, bottom: 1.5m/s)

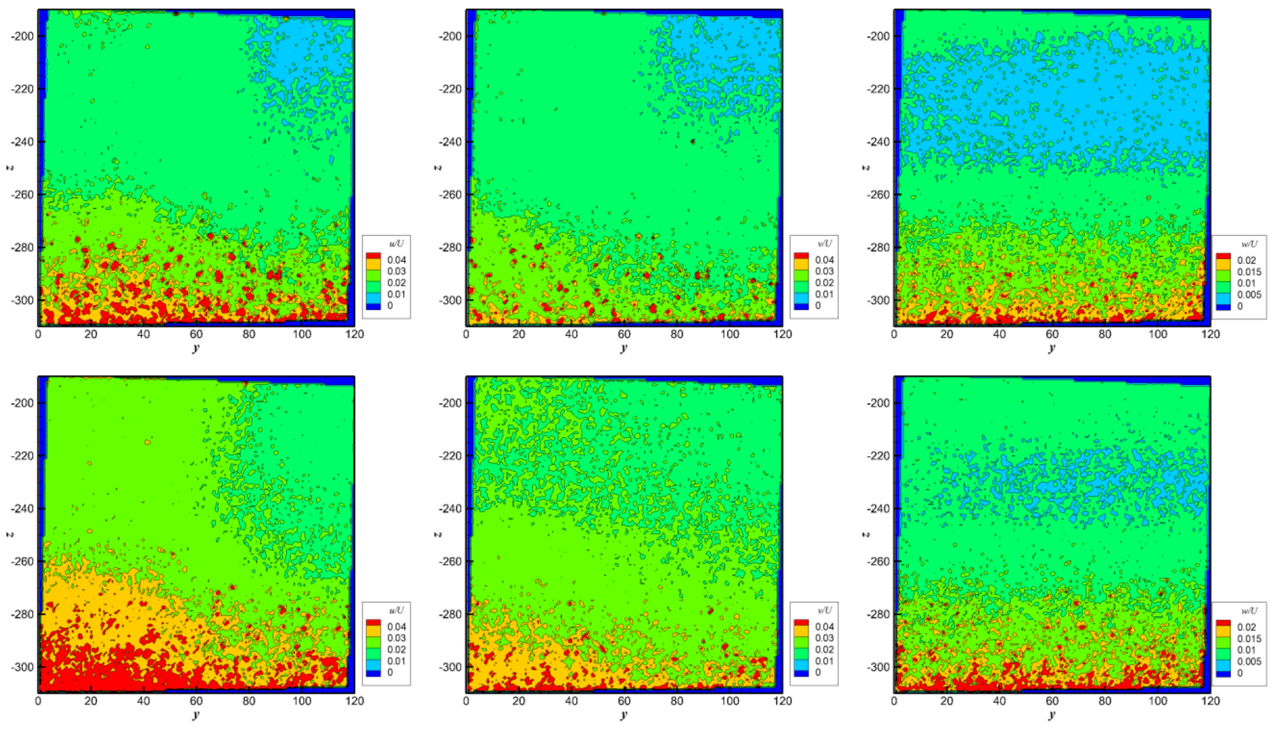

**Figure 7** RMS of velocity distribution for y-z plane (top: 1.0m/s, bottom: 1.5m/s)

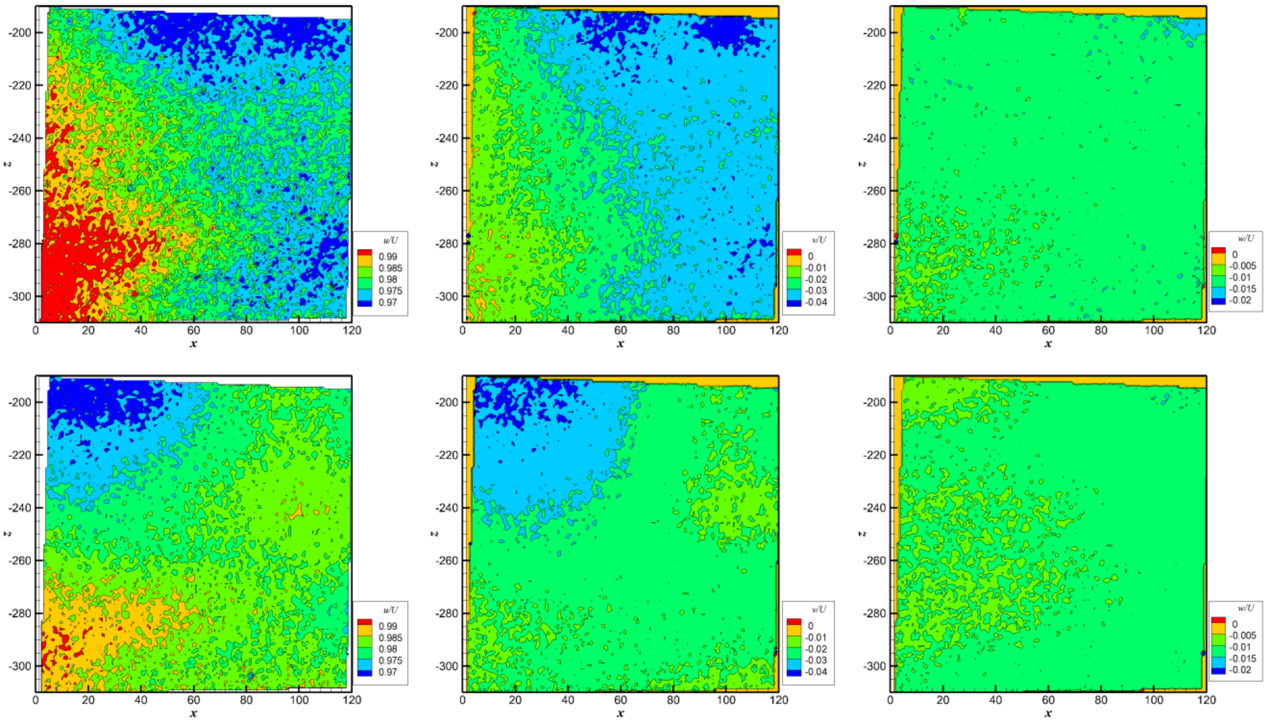

**Figure 8** Velocity distribution for x-z plane (top: 1.0m/s, bottom: 1.5m/s)

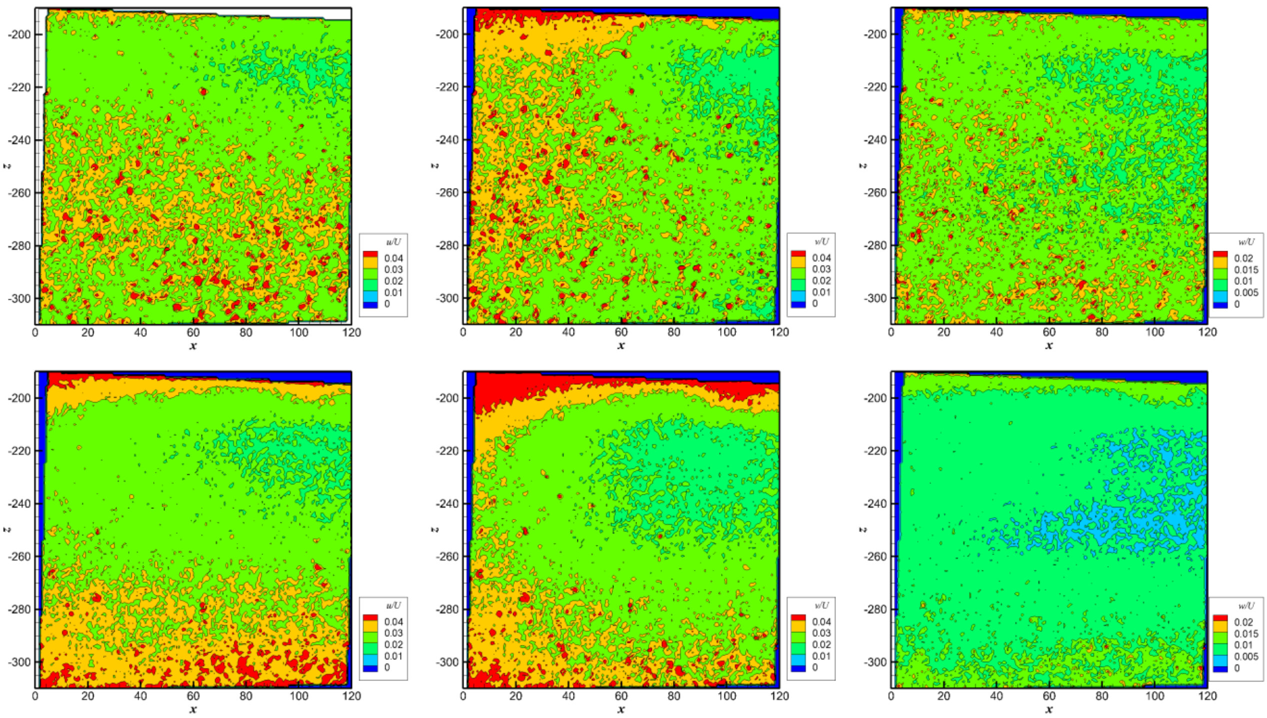

**Figure 9** RMS of velocity distribution for x-z plane (top: 1.0m/s, bottom: 1.5m/s)

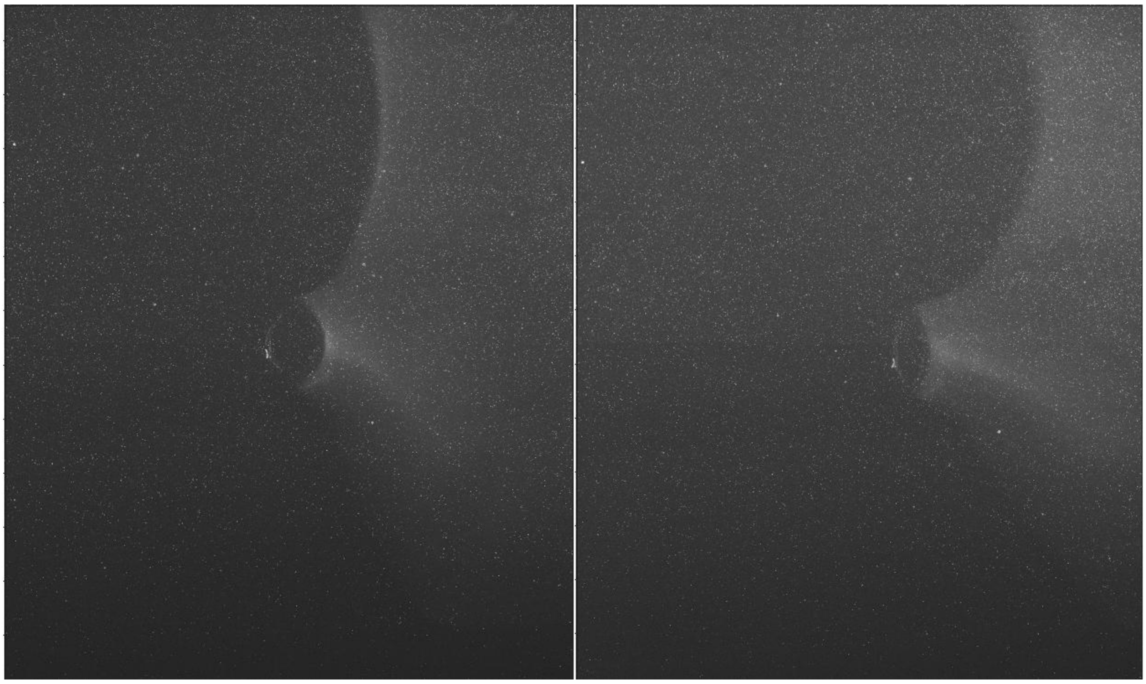

**Figure 10** Particle images (left: camera 1, right: camera 2)

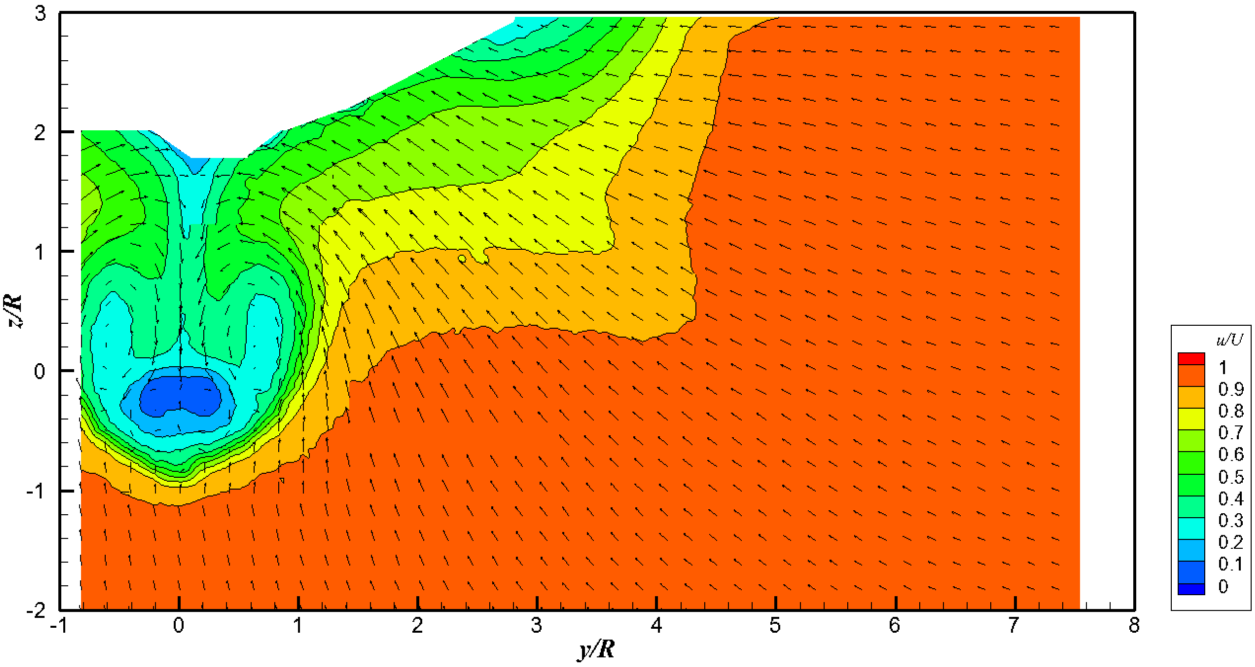


**Figure 11** Velocity field at propeller plane

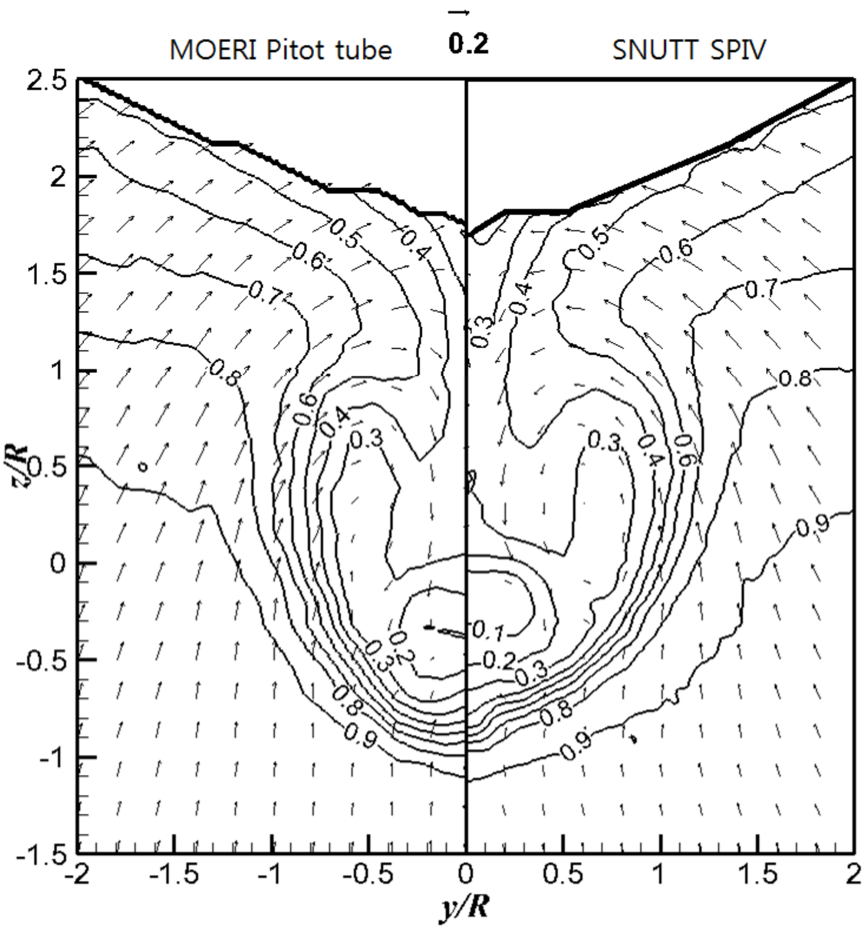


**Figure 12** Nominal wake results of Pitot tube and SPIV

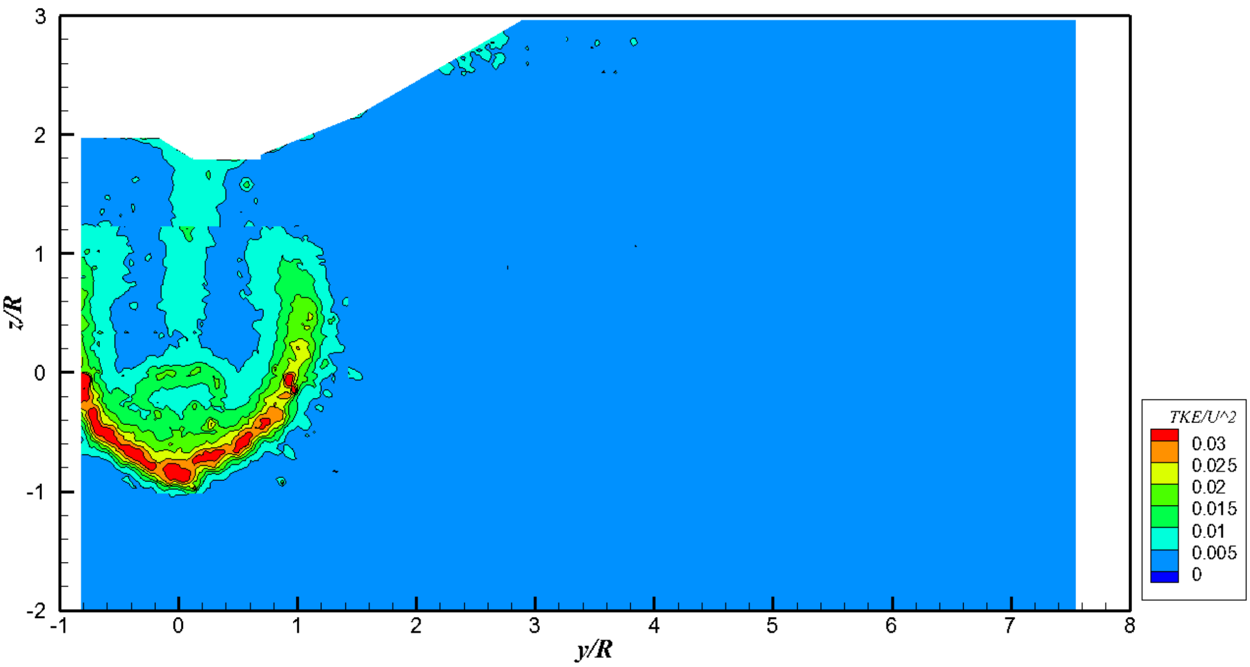


**Figure 13** TKE distribution

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