PIV/LIF Measurement of Wall Turbulence Modification by Microbubbles

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It is known that local skin friction can be reduced by injecting microbubbles into the turbulence boundary layer, however, mechanism of the reduction has never been revealed so far. In the present study, the objective is to understand characteristics of turbulent flow field containing the microbubbles with experimental approach in order that the mechanism for the reduction is elucidated clearly. In order to measure the flow with the microbubbles, a PIV and LIF combined method was introduced. Measurements were carried out for a horizontal channel flow with microbubbles by which the skin friction is reduced, and it was discussed modifications of the wall turbulence due to injecting the microbubbles.

Introduction

For local skin friction reduction, a several methods have been proposed. It is known that injecting microbubble into the turbulent boundary layer of liquid developed on a body surface is one of the methods to reduce the skin friction. Madavan et al. (1985) investigated that efficiency of the reduction with microbubbles could reach up to 80%. We also have investigated the skin friction reduction of a ship by injecting the microbubbles onto its bottom hull surface, and effect of reduction has been confirmed (Kodama et al, 2000).

The method of the reduction is expected to apply to practical use, and for the application and design with such drag reduction device with microbubbles, it is necessary to understand a mechanism of the reduction. However the mechanism of the reduction by the microbubbles has never been elucidated clearly yet. Many investigations on the drag reduction by the microbubbles have been conducted in terms of measurement of hydrodynamic force. Measurements for the flow field where the microbubbles reduces the skin friction have been rarely done, because of difficulties that the flow with the microbubbles is a multi-phase flow consist of liquid and gas. Therefore properties of the flow field with the microbubbles have never been obtained, especially what happens in liquid phase around the microbubbles.

The objective of our project is to reveal the mechanism of the skin friction reduction for control the turbulence. In the present study, we focus on investigating a wall turbulent modification by the microbubbles, where the skin friction is actually reduced in a horizontal channel. Many researches on rising bubbles have been conducted and the microscopic mechanism of turbulent modification of them is being elucidated with effective experiments (Hishida et al. 2001). In order to obtaining velocity distribution of the horizontal flow, we introduced a measurement system combined Digital Particle Image Velocimetry (DPIV) and Laser Induced Fluorescence (LIF) (Nagaya et al, 2001). It has been developed in the research of measurements for bubbly flows so that the liquid phase can be extracted from the flow with the microbubbles.

Measurements for the flow containing the microbubbles were carried out with changing a void ratio. We discussed modifications of the velocity profile, turbulent intensity and Reynolds sheer stress given by the microbubbles with statistical analysis. At the results of analysis, it was found that the microbubbles could decrease Reynolds sheer stress.

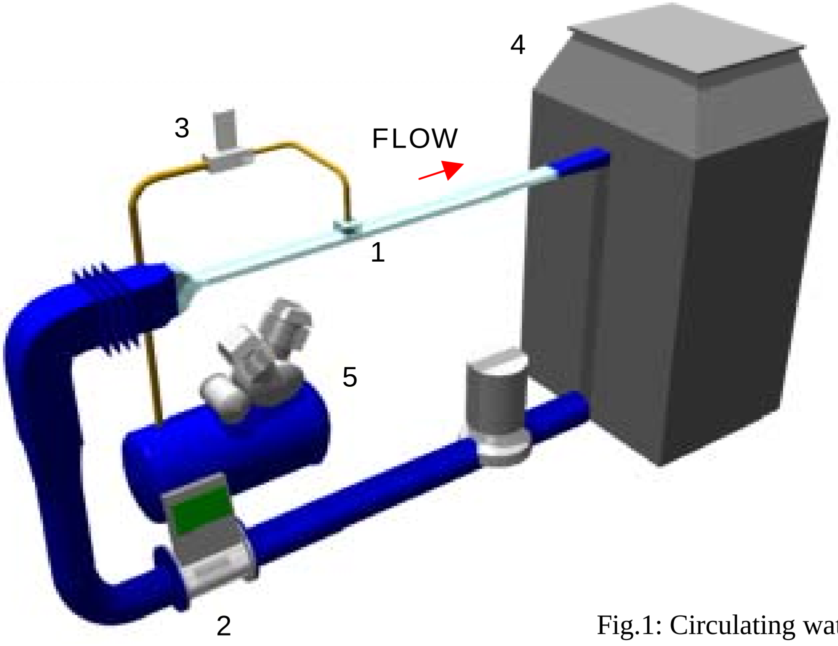


Fig.1: Circulating water tunnel

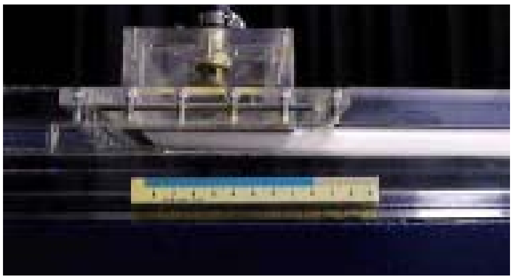


Fig.2: Picture of injection of microbubbles

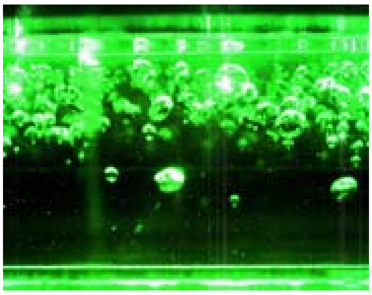


Fig.3: Picture of microbubbles injected into the channel

Experimental method

Circulating water channel

Experiments are carried out on a circulating water tunnel as shown in Fig.1. The tunnel has a horizontal channel section with following dimensions, channel height h=15mm, channel width b=100mm and length of the test section 3000mm, respectively. It has capability to realize the flow velocity 12m/s and equip a dump tank to remove the bubbles from water; therefore we can conduct the measurement on this channel continuously under the condition on fully developed turbulence. The mean flow velocity U is determined by controlling water flow rate Q_w. The microbubbles are injected into the channel through an array-holed plate, as shown in Fig. 2, which is mounted on upper wall at the 1028mm downstream position from a beginning position of the channel. Airflow rate Q_a of injected microbubbles is controlled by a mass flow meter. Bulk void ratio α of the microbubbles is given by $\alpha = Q_a / (Q_a + Q_w)$. In Fig.3, it is found that the microbubbles are concentrate into upper region in the channel due to own buoyancy. The diameter of the microbubbles is approximately 1mm.

PIV/LIF system

A Digital Particle Image Velocimetry (DPIV) system is introduced to measure a turbulent flow field in this study. A schematic sketch of the present system is shown in Fig.4. A double pulse Nd:YAG laser illuminates a sheet light from a bottom side of the channel along the streetwise. The Nd:YAG laser has following spec, the

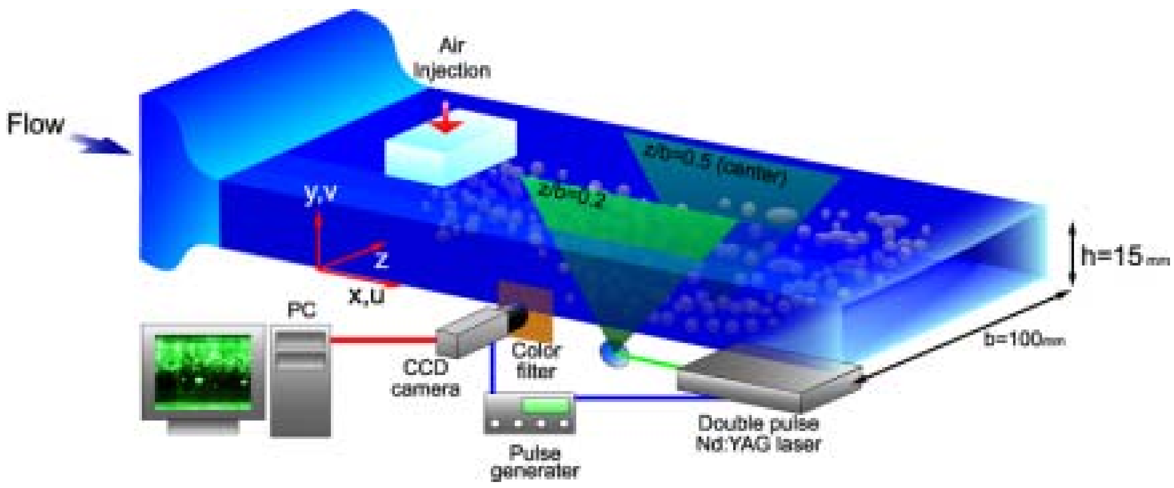
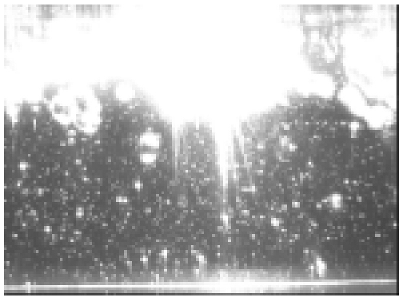
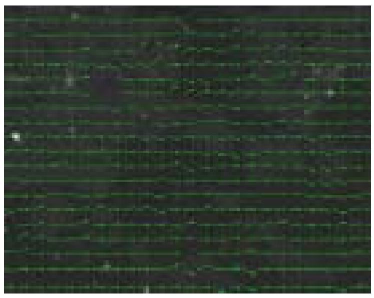


Fig.4: Schematic sketch of PIV measurement system



a) Image of conventional tracer



b) Image of LIF tracer and vectors

Fig.5: Comparison of captured images

power 30mJ, the wavelength 532nm and pulse width 5ns, respectively. A CCD camera, which is 1 million pixel and 8-bit, captures images and it is connected to a PC. Illumination of the laser system and exposure of the camera are synchronized by a pulse generator, and it can take 30 frames (15pairs) per second.

In the case of applying the PIV for the flow containing the bubbles, however, a strong reflection of laser light is occurred on the surface of the microbubbles, so that the CCD device is saturated. Thus it is hard to capture the image of tracers especially at the field around the microbubbles. Therefore to avoid such difficulty, Laser Induced Fluorescence (LIF) technique is applied to the measurement as fluorescent tracer particles. Rhodamine-B as the fluorescence dye polymerizes to give particles, and the diameter of the LIF tracer particles is approximately 1 ~ 10 μm and a specific density is 1.02. The wavelength of the fluorescence emitted from the LIF tracer is longer than that of the reflected laser light. The reflected light is removed through a color filter, and the CCD camera can capture the image with only the fluorescence from the LIF particle in a liquid phase. In Fig.5, a comparison of captured images between conventional tracer and LIF tracer is shown. In the image of the conventional tracer, it is difficult to analyze due to strong reflection on the bubble surface. On the other hand it can be seen that the reflection is removed so it can be analyzed. Finally we use the image of the fluorescence for PIV analysis. In this system, image data are analyzed by cross-correlational technique, and we can obtain the velocity vector at each location in the liquid phase (Tokuhiro et al., 1998).

Results and discussions

For the present study, we conducted measurements under the condition as shown Table 1. In order to detect influences of the microbubbles on the flow, bulk void ratio α was given a several values. It has been found that the local skin friction is reduced most effectively at such velocity range, where approximately over 20% reduction is achieved on α=7% condition as shown in Fig.6. Fig.7 shows a typical result of local void ratio distribution in the channel. The abscissa is the local void ratio and the vertical axis is relative position y/h in the channel. It is found that the microbubbles are concentrated in a upper region in the channel due to their own buoyancy. And a peak value of the local void fraction is obtained at approximately y/h = 0.8 position.

The measurements were carried out at the point of 500mm toward downstream. On the other hand, a laser sheet was illuminated on z/b = 0.2 plane, because it is hard to obtain images in a center of the channel due to overlapping of the bubbles hides the tracer.

Table.1: Experimental conditions

Parameters	Value
Bulk velocity, U	5.0m/s
Reynolds number, Re	28600
Reynolds number, $Re\tau$	1200
Bulk void ratio, α	0%, 1%, 3%, 5%, 7%

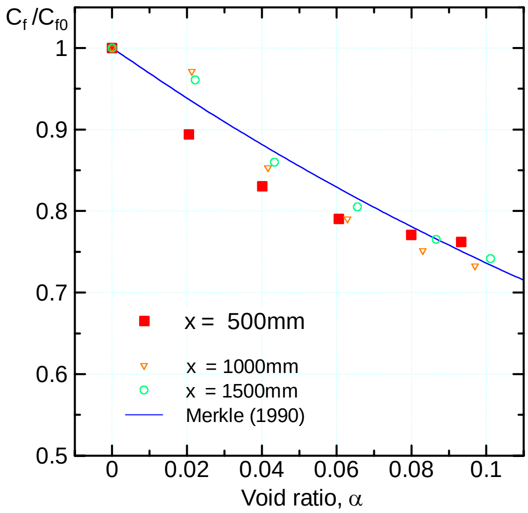


Fig.6: Result of skin friction reduction at U=5.0m/s

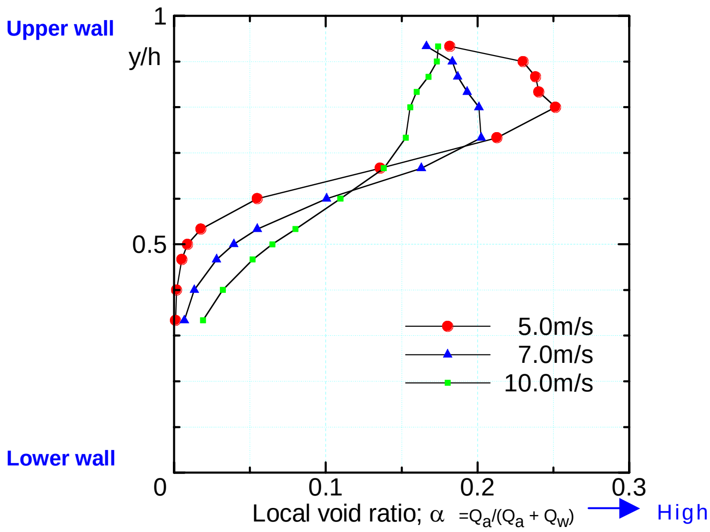


Fig.7: Distribution of local void ratio of microbubbles

<u>Velocity profile</u>

Fig.8 shows profiles of the average velocity distribution of u between the cases for each void ratio. As the void ratio increases, a velocity gradient becomes smaller in a region near the upper wall, where the local void ratio is high. On the other hand, in the region of y/h = 0 ~ 0.5, the velocity gradient is getting higher as the void ratio increases.

On the present configuration, the bulk velocity of water becomes higher with increases of the void ratio. Because water flow rate is fixed constantly and bubbles are injected into the channel. The increase of the bulk velocity U_b given by measured velocity distribution is shown in Fig.9. Although the present results were obtained at the position of z/b=0.2, corrected profiles of the velocity distribution based on the changes of the bulk velocity U_b are shown in Fig.10. It can be seen that the flow is transited to laminar flow in the region of y/h = 0.5 ~ 1.0. It suggests that skin friction is reduced. On the other hand, the profiles in the region of y/h = 0 ~ 0.5 is approximately same with each other.

Profiles of the velocity distribution v are shown in Fig.11. It can be seen that upward flow is measured in the region of y/h = 0.8 ~ 1.0, and the value is getting larger as the void ratio increases. It is considered that rising of microbubbles induces such upward velocity. On the present condition of the bubble size, the upward flow velocity is approximately reasonable with a rising velocity of the microbubbles.

Turbulent intensity

Profiles of the turbulent intensity u_{rms} and v_{rms} for various void ratios are shown in Fig. 12 and 13. They are RMS value of u and v and normalized by a friction velocity u_τ. In both results, the turbulent intensity becomes larger as the void ratio increases in a region of y/h = 0.5 ~ 1.0. In the region of y/h = 0 ~ 0.5, where the microbubbles are rarely contained, there are no remarkable differences.

In each case, a peak values of the fluctuation are obtained at the position of approximately y/h = 0.85. According to the result of the local void ratio distribution, its peak value is given at y/h = 0.8 ~ 0.9 on U = 5.0 m/s condition. It is considered that such fluctuation is induced by motion of the microbubbles especially due to its buoyancy. However, in such a horizontal flow, a relative velocity of the microbubbles in the flow direction must be almost zero. Therefore data of the relative motion and deformation of the microbubbles which is simultaneously coupled with the flow field of liquid phase is necessary. We are conducting such simultaneous measurements by coupling with Infrared Shadow Technique (IST), which can capture shape of the bubbles. We are going to discuss a relationship between turbulence modulation and bubble motion.

Reynolds stress

Fig.14 shows profiles of the Reynolds stress $u'v'$ for various void ratios, where u' and v' mean fluctuations of u and v respectively. It is found that the value of $u'v'$ is getting smaller as the void ratio increases. Especially in α=3%, 5% and 7% cases, the values become negative in y/h = 0.7 ~ 1.0 region. The peak value of them are

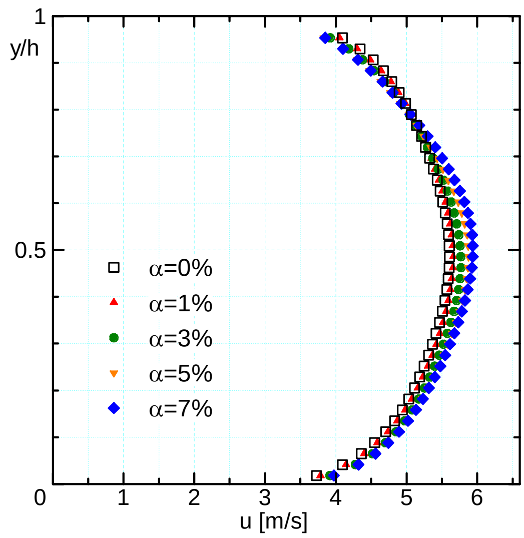


Fig.8: Profiles of velocity distribution u

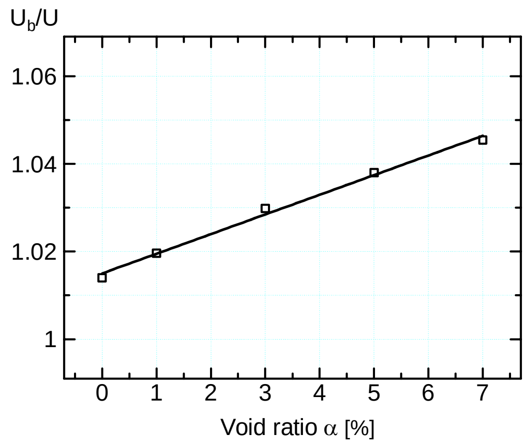


Fig.9: Changes of bulk velocity due to injected microbubbles

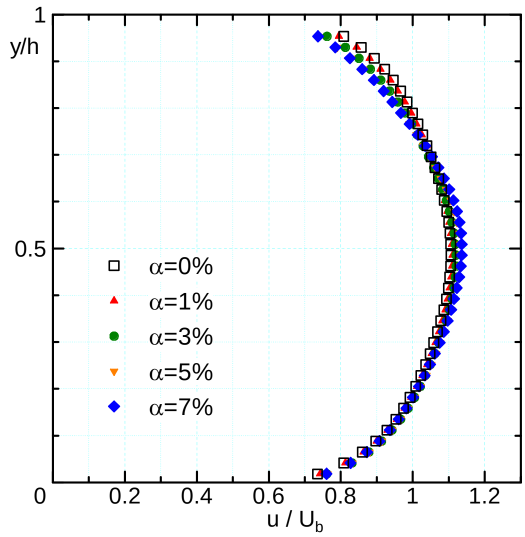


Fig.10: Corrected profiles of velocity distribution u based on bulk velocity

obtained close to the upper wall, it is not corresponding to a tendency of the result of the turbulent intensity u_{rms} and v_{rms}. It could be a suggestive result to understand characteristics of the flow where the skin friction is reduced. It is had to consider how the budget of turbulence energy is balanced with the negative Reynolds stress.

To detect such tendency of Reynolds stress, Fig.15 shows a comparisons of Probability Density Function (PDF) contours for *u'* *vs.* *v'* at certain positions between a result of α=0% case and that of α=7%. In the region of *y/h* = 0.7 ~ 1.0, the distribution of α=7% case is more broad than that of α=0% case, which is corresponding to the results of the turbulent intensity *u'* and *v'*. And tendency of the correlation is different between the results of α=0% and that of α=7% in such region. Here, according to the comparison at *y/h*=0.95, in the result of α=0% case, a positive correlation between *u'* and *v'* is obtained. On the other hand, in that of α=7% case, a broad negative correlation between them appears. It could suggest that the motion of bubbles induces a *u*-*v*-connected fluctuation. Thus it needs data of bubble's motion simultaneous with the flow.

Conclusion

In order to detect a phenomenon of skin friction reduction by microbubbles, we carried out PIV/LIF measurements on a horizontal channel flow containing the microbubbles for various void ratios of the microbubbles. At the result of statistical analysis, it was obtained that the turbulent fluctuation both of *u'* and *v'* becomes larger as a void ratio increases. In terms of Reynolds stress, negative values were obtained when void ratio is high. We will investigate where such turbulence modification comes from in the future scope. To obtain an instantaneous information of bubble's motion and position simultaneous with the flow is necessary. And the present results could be also suggestive for the numerical approaches of drag reduction, so we are cooperating with them each other so that a mechanism of the skin friction reduction is elucidated.

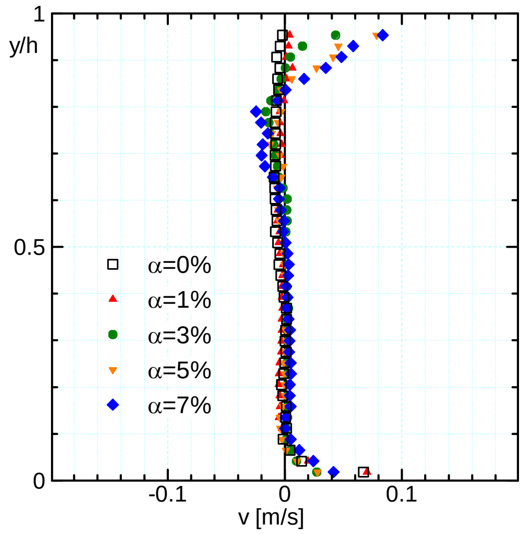


Fig.11: Profiles of velocity distribution *v*

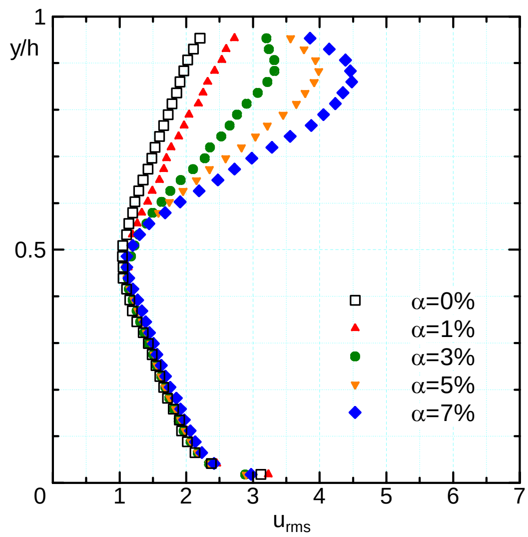


Fig.12: Profiles of distribution of turbulent intensity u_{rms}

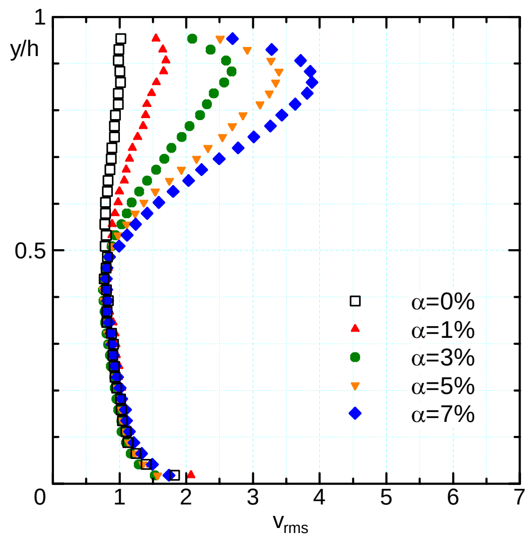


Fig.13: Profiles of distribution of turbulent intensity v_{rms}

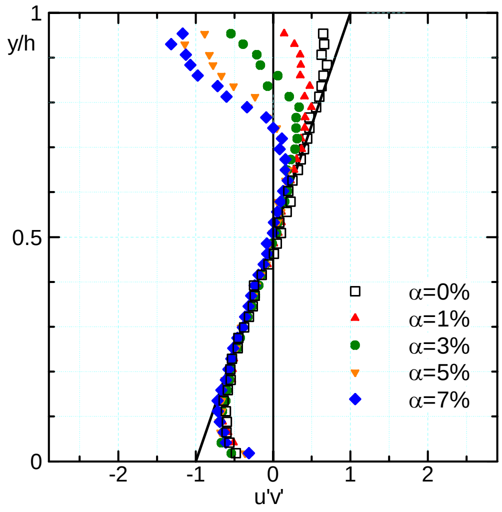


Fig.14: Profiles of Reynolds stress *u'v'*

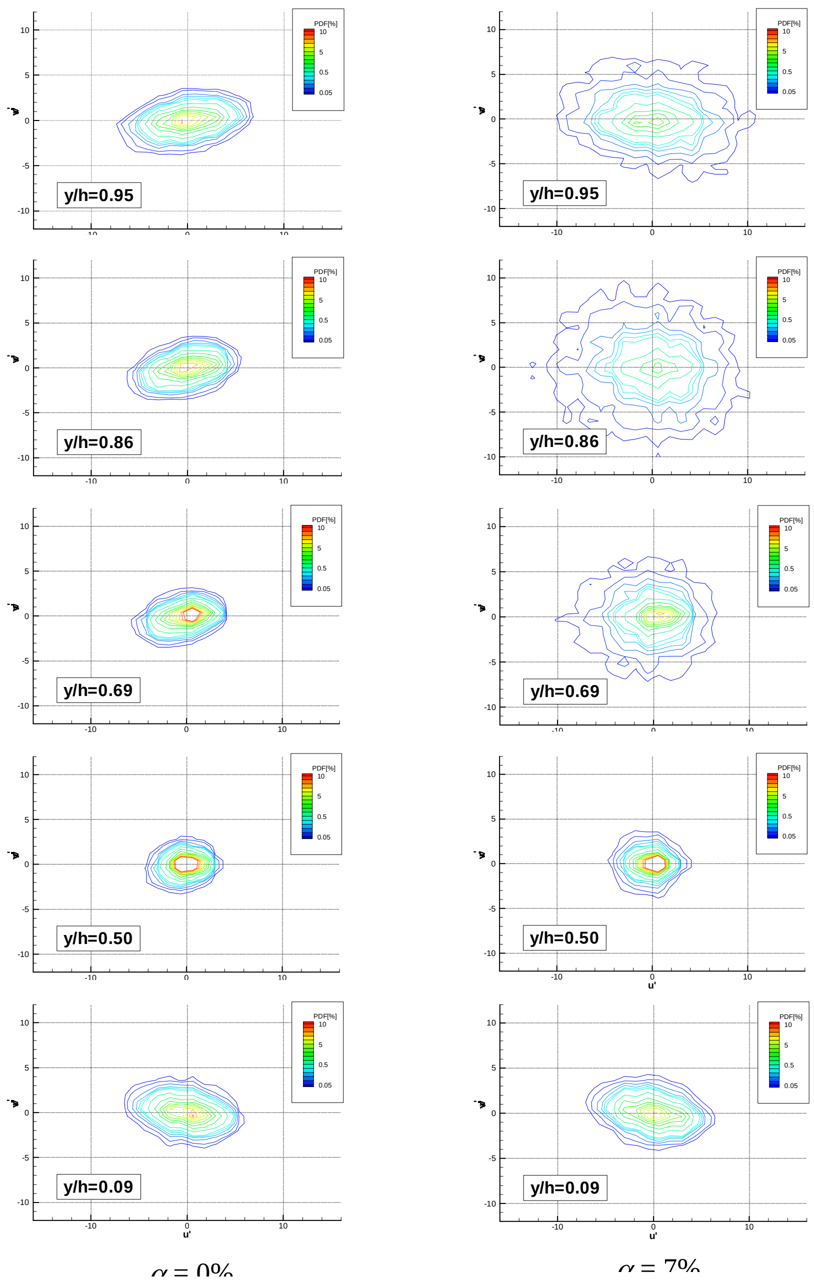


Fig.15: Comparison of PDF contour of *u'* *vs.* *v'* correlation between *a*=0% and

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