PIV Measurement of Turbulent Mixing Layer Flow with Polymer Additives

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Abstract. Turbulent mixing layer flow with polymer additives was experimentally investigated by PIV in present paper. The velocity ratio between high and low speed is 4:1 and the Reynolds number for pure water case based on the velocity differences of two steams and hydraulic diameter of the channel ranges from 14667~73333. Flow field and turbulent quantities of turbulent mixing layer with 200ppm polymer additives were measured and compared with pure water mixing layer flow. It is shown that the dynamic development of mixing layer is greatly influenced by polymer additives. The smaller vortices are eliminated and the coherent structure is much clearer. Similar with pure water case, Reynolds stress and vorticity still concentrate in a coniform area of central part of mixing layer and the width will increase with the Reynolds number increasing. However, compared with pure water case, the coniform width of polymer additives case is larger, which means the polymer additives will lead to the diffusion of coherent structure. The peak value of vorticity in different cross section will decrease with the development of mixing layer. Compared with pure water case, the vorticity is larger at the beginning of the mixing layer but decreases faster in the case with polymer additives.

1. INTRODUCTION
After the phenomenon that flow friction of polymer solution was smaller than pure solvent under the unsteady turbulence state had been found by Toms (1948), resistance reduction with polymer additives has been widely applied in many fields, such as ship transportation, petroleum transportation and fluids pipeline conveying because it is very important to save energy and protect ecological environment. After almost 60 years’ study on this phenomena, the research direction has changed a lot. At the very beginning, researches were concentrated on the aspect that they conjecture the turbulent influence with polymer additives by studing motion characteristics of polymer molecular in shear flows and elongational flows (Lumley J L, 1969; Rabin Y et al., 1989). Later, Virk P S. (1967) found that onset of drag reduction occurs at a well-defined wall shear stress related to the random-coiling effective diameter of the polymer, and the maximum drag reduction possible is limited by an asymptote that is independent of polymer and pipe diameter. Gordons R J. (1970) showed the effects of turbulent coherent structures with addition of polymer, and he thought that the intensity of bursting process of turbulent boundary layer was weaken with polymer additives. Then, several researchers also put forward their theories such as pseudo-plastic behavior, turbulent fluctuation inhibition, and viscoelasticity, etc(Shao, 2001). However, the conclusion on the mechanism of drag reduction by polymer additive wasn’t clear enough.
It is well known that the mixing layer is a classical free shear flow with large eddy coherent structure..
It will be very helpful to study the influence of polymer additives on turbulent fluctuation and coherent structure. Hibberd (1982) measured the mixing layer with polymer additives by LDA, and found that small-scale structures were decreasing and turbulent coherent structures were more clear. Riediger (1989) found that the survival time of coherent structure was longer and the increasing of momentum thickness was inhibited. SHAO (1998) reported the influence of polymer addition on coherent structure and turbulent fluctuation, and found that the increasing of momentum thickness was slower. However, no quantitative conclusions were reported up to now.

In present paper Particle Image Velocimetry (PIV) will be used to measure the distribution of velocity, Reynolds stress and average vorticity to get the quantitative information of the turbulent mixing layer with polymer additives and compared with pure water case to study the drag reduction mechanism by polymer additives in turbulent flow.

2. EXPERIMENTAL EQUIPMENT
All the tests were done in the vertical channel of mixing layer experimental system. By using a special designed splitter, a vertical inflow was separated into two streams of flow with designed different velocity to form the mixing layer at the end of the splitter (Guo F D. et al., 2007). In order to visualize the mixing layer, a PIV system supplied by La Vision GmbH is adopted. The PIV system integrates a double pulsed, 15 Hz, 532 nm, 200 mJ Nd-Yag lasers including sheet optics to generate a light sheet from the laser beam. The focus and the thickness of the laser sheet can be adjusted via the laser-sheet optics and a thickness of approximately 1mm is used throughout the experiment. Silver-coated hollow glass balls with the diameter size distribution of 8-12µm and a density of 1.1g/cm³ are used as tracer particles. Each illumination of the measurement area is recorded using two (2D) ImagerPro4M CCD cameras (8 bit, 15 Hz) with a resolution of 2048 × 2048 pixels.

In present paper, the velocity ratio between high and low speed is 4:1 and the Reynolds number for pure water case based on the velocity difference of two streams and hydraulic diameter of the channel ranges from 14667~73333. Odium salicylate (NaSal) was added into the pure water and the concentration is 200ppm. The typical test conditions were shown in Tab 1.

| Tab 1. Test conditions
|:---|:---|:---|:---|
| $u_h$ (m/s) | $u_l$ (m/s) | $\Delta u = u_h - u_l$ (m/s) | Water Re = (Re $ud$) / $v$ |
| 0.33333 | 0.08333 | 0.25 | 14667 |
| 0.66667 | 0.16667 | 0.50 | 29333 |
| 1.33333 | 0.33333 | 1.00 | 58667 |
| 1.66667 | 0.41667 | 1.25 | 73333 |

3. RESULTS AND DISCUSSION
In this section, we analyze the typical test condition in Tab 1 and discuss the variations of turbulent quantities. In the following figures, the origin is the starting point of the mixing layer (centre of the splitting plate end). The $x$ axis is along the downstream direction, and $y$ axis is from the low speed side to the high speed side along the vertical flow direction. $x^*$ and $y^*$ are the non-dimensional length normalized by half width of the channel.

3.1 Velocity
At first, we checked the average velocity profiles along the downstream direction in different cross-section of the mixing layer shown in Fig. 1 (Reynolds number of pure water case is 73333). It can be seen that the velocity ratio between high speed side and low speed side is 4:1. Besides, it was well consistent with the designed ratio for both of the pure water case and polymer addition case. Through the comparison between the data of two cases, we can find that the wake caused by the splitter plate are stronger for the case with polymer additives.
Fig. 2 shows the velocity vector distribution in the mixing layer which is given by
\[ U = u - \left( \bar{u}_h + \bar{u}_l \right)/2 \]
and the velocity difference between high speed and low speed is 0.5 m/s. Apparently, we can see the coherent structures in both of two conditions. Compared with pure water case, the vortex structure of the polymer case was enhanced, so it was more clear and larger. Furthermore, the large eddy also rolled up earlier. With the increasement of velocity difference, these influence is more obvious. And there are similar results for other conditions with different Reynolds numbers.

\[ \Delta u = 0.5 \text{ m/s} \]

3.2 Reynolds Shear Stress

Fig. 3 gives the Reynolds shear stress \( -\bar{u}'v' \) with various velocity differences in the mixing layers. It is obvious that Reynolds shear stress with polymer additives appears a peak value near the central line of the mixing layer. Moreover, similar with pure water case, it was concentrating in a coniform area of central part of mixing layer and the width of this area will increase with increasing of velocity difference.
difference. Furthermore, Reynolds shear stress increases along the downstream direction but decreases with the increase of Reynolds number, and there is a trend that it is developing to the low speed side. Compared with pure water case, the coniform width of polymer additives case is larger, which means the polymer additives will lead to the diffusion of coherent structure. These rules can be reflected more directly in Fig. 4. Profile of Reynolds shear stress between pure water and polymer at the same cross-section and the same velocity difference can be compared in this picture. It was clear that the coniform width and the value for polymer additives case are larger.

3.3 Vorticity

The flow field distribution of average vorticity was shown in Fig. 5. It indicates that the average vorticity in the flow field increases with the velocity difference and Reynolds number increasing, while it decreases with the development of the mixing layer along the streamwise. The peak value of average vorticity concentrated on the central area of mixing layer along streamwise. Different with pure water case, coniform width of polymer additives case is larger, and the value of vorticity is greater, too.

To reveal the average vorticity variations more clearly, the peak value of average vorticity along the main flow direction was given in Fig. 6. For the pure water case, the average vorticity decreases directly. But in the polymer case, the peak value of average vorticity increases at the very beginning of the mixing layer, and then it decreases. Compared with pure water case, the average vorticity is larger at the beginning of the mixing layer but decreases faster in the case with polymer additives. It means that attenuation rate of polymer case is higher. The reason is that the viscosity of polymer fluid is greater than pure water, which will result in the reduction of velocity fluctuation in y direction. Then, the velocity gradient in flow field will decrease and there will be a faster decay of vorticity in polymer case. For the other velocity difference not shown here, the peak value of average vorticity are similar with Fig 6.
4. CONCLUSIONS
In order to reveal the mechanism of drag reduction by polymer addition, turbulent mixing layer flow with polymer additives was experimentally investigated by PIV in present paper. Flow field and turbulent quantities of turbulent mixing layer with 200ppm polymer additives were measured and compared with pure water mixing layer flow. Our experiment indicates that large coherent vortex structures exist in both of pure water case and polymer additives case, and they are enhanced when polymer was added to the water. We found that Reynolds stress and vorticity are concentrated in a coniform area of central part of mixing layer and the width of peak value area will increase with increasing of velocity difference. And values of vorticity and Reynolds stress are increased when polymer was added into the water. The peak value of average vorticity of polymer additives case decreased faster than pure water one.

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