PIV Measurement of Turbulent Bubbly Mixing Layer Flow with Polymer Additives

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Abstract. Based on experimental investigation of single-phase turbulent mixing layer flow with polymer additives, bubbly mixing layer was experimentally investigated by PIV. The velocity ratio between high and low speed is 4:1 and the Reynolds number based on the velocity difference of two streams and hydraulic diameter of the channel ranges is 73333. Gas bubbles with about 0.5% gas fraction were injected into pure water mixing layer with/without polymer additives from three different parts at the end of the splitter plate. The comparison between single phase and bubbly mixing layer shows clearly that the dynamic development of mixing layer is great influenced by the bubble injection. Similar with single phase, the Reynolds stress and vorticity still concentrate in a coniform area of central mixing flow field part and the width will increase with increasing the Reynolds number. Mean Reynolds stress will decrease with bubble injection in high Reynolds numbers and the decreasing of Reynolds stress with polymer additives is much more than pure water case.

1. INTRODUCTION

It is well known that pressure drop from frictional losses can be reduced with gas injection when a shear-thinning fluid is flowing through a pipeline. Ward and Dallavalle (1954) found this phenomenon earliest when they injected air into clay suspensions flowing in the laminar regime. Following experiments about the press drop indicated that hydraulic characteristics of two-phase non-Newtonian flow was quite different with Newton fluid, and the pressure in pipeline dropped a lot (Chhabra et al., 1983; Dziubinski, 1995; Kaminsky, 1998). This phenomenon is broadly applied in various fields such as long distance transportation, drag reduction of large-scle ships, tertiary oil recovery, and reducing the viscous friction of blood flowing to cure the coronary heart disease, etc. Hence, it is very important to study the flow characteristics and drag reduction mechanism through the injection of gas bubbles in conjunction with polymer additives.

Mixing layer is an classical free shear flow with large coherent vortex structure and it is very helpful to reveal mechanism of drag reduction by studying the influence of turbulent fluctuations and coherent structure with addition of bubble and polymer. Based on the research of pure water turbulent mixing layer(Guo et al., 2007), PIV will be used to investigate the influence of polymer addition and bubbles injection on mixing layer coherent structures and turbulent quantities. It will be the basis to study the interaction between non-newtonian fluids with bubbles, and the drag reduction mechanism with polymer and bubbles in turbulent flow.
2. EXPERIMENTAL SYSTEM

As shown in Fig. 1a, a vertical inflow was separated into two streams by a specially designed splitter (Fig. 1b) with designed high and low velocity to form the mixing layer. In present paper the velocity ratio is 4:1, velocity difference is 1.25m/s and the Reynolds number for pure water case is 73333 defined as \( \text{Re} = \frac{\Delta u d}{\nu} \), where \( \Delta u \) is velocity difference of two streams and \( d \) is hydraulic diameter of the channel. Gas bubbles were injected from high speed side, low speed side and end of splitter with 0.2mm stainless steel tube from a nitrogen bottle. The distance between bubble tube and the end of splitter is 10mm so the disturbance of formation of mixing flow by the bubble injection can be avoided. Odium salicylate (NaSal) was added into the water tank and the concentration is 200ppm. Mixing layer flow with/without polymer additives and bubble injection are measured by a PIV system supplied by La Vision GmbH and compared with pure water cases. 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.

3. RESULTS AND DISCUSSION

In this section, we analyzed the turbulent flow field of mixing layer with bubbles and polymer additives with velocity difference between high speed and low speed 1.25m/s and Reynolds number is 73333. The fluctuation of turbulent coherent structure and statistics were also discussed, when bubbles and polymer were added into the flow field. The diameter of the bubbles was from 0.5mm to 2mm, and the void fraction defined by \( \alpha = \frac{A_g}{A} \) is 0.5%, where \( A_g \) is flow rate of gas and \( A \) is total flow rate of gas and liquid. 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 down stream direction, and \( y \) axis is from the low speed side to the high speed side. \( x^* \) and \( y^* \) are non-dimensional length normalized by half width of the channel. Fig. 2a and 2b show the original image of polymer solution mixing layer with/without bubble injection taken by PIV, respectively. The cyan region at the left and central of Fig. 2 is splitter. Because the intensity of PIV incident light is different, the colour of background in Fig. 2a is various.

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**Fig.1 Experimental system**

1. upstream flow
2. flexible hoses
3. flow calming box
4. contraction connection
5. splitter plane
6. turning perforated plate
7. calming material
8. gas injection string in high speed side
9. gas injection string in low speed side
10. gas injection string in central part
11. PIV CCD
12. test section
13. downstream water tank
14. back flow pipe
Fig. 2a showed that the distribution of tracer particles in flow field is homogeneous. In Fig. 2b, it can be seen that bubbles are injected from low speed side, high speed side and the end of splitter simultaneously. The bubbles which injected from high speed side are concentrating in high speed side, and the bubbles from low speed side are diffusion. However, the bubbles from the splitter end aggregative in the central part of mixing layer and migrate to low speed side. The background is painted to black to avoid the reflection. Finally, useful flow information can be contained by processing these original images.

3.1 Velocity

The profile of average velocity along the down stream direction on same cross-section was shown in Fig. 3. It can be seen that the distribution of velocity was influenced by bubbles injected into both pure water and polymer case. The magnitude of its variation is based on the difference between the initial speed of injected bubbles and the local fluid velocity. It is clearly shown that the modification of pure water case is more obvious than polymer case.

Fig. 4 gave the distributions of instantaneous velocity vector \( U = u - (\bar{u} + \bar{v}) / 2 \) of pure water case, pure water with polymer additives case, pure water with bubbles injection case and the case with both bubbles and polymer additives. The formation, rolling up and evolution of coherent structure can be seen clearly in pure water case. When polymer is added into the water, the coherent structures are clearer, and the small scale vortices are eliminated. When bubbles are injected, the formation of vortex structures is hindered because of the bubbles distribution, and the coherent structures are weakened. However, when bubbles are injected into polymer mixing layer, the coherent structures are re-enhanced, and the large eddy is clear and large again.
3.2 Reynolds Shear Stress

Distributions of Reynolds shear stress \( (\overline{u'v'})/(u'_e - u_e)^2 \) were given in Fig. 5. Similar with pure water case, Reynolds shear stress for all cases are still concentrating in a coniform area of central part of mixing layer and the width of peak value area will increase along the flow direction. When bubbles are injected into the flow field, it is obviously that Reynolds shear stress decreases in both pure water case and polymer case.

![Fig. 4 Instantaneous velocity vector (\( \Delta u=1.25 \) m/s)](image)

![Fig. 5 Distribution of Reynolds shear stress](image)

Reynolds shear stress of pure water and polymer with and without bubble injection on the same cross-section was compared in Fig. 6. Reynolds stress decreases a lot with bubble injection and the reduction of Reynolds stress when bubbles are injected into polymer solution is much more than pure water case. For polymer case, the increase of virtual viscosity may be greater to pure water. Therefore, the decrease of Reynolds stress will be larger. With the injection of bubbles, the effective viscosity is increasing. That may cause the lessening of velocity fluctuation, so the Reynolds stress decreased.

![Fig. 6 Profile of Reynolds shear stress (x*=1)](image)
3.3 Vorticity

Fig. 7 gave the average vorticity distribution for all cases. Similar with Reynolds shear stress, the average vorticity is also concentrating in a coniform area of central part of mixing layer. Further more, it decreases with the development of mixing layer along the down-stream direction. With injection of bubbles, the average vorticity decayes, and the coniform area becomes smaller. The vorticity decreases faster because the turbulence is trending to isotropic with the addition of bubbles. It means that the velocity fluctuation in the vertical main stream direction are decreased to balance the disturb in this aspect.

![Fig. 7 Average vorticity field](image)

The peak value of vorticity along down stream direction is shown in Fig. 8 for all cases to reveal the variations of average vorticity. For single phase, the average vorticity decreases directly for the purewater case. But for polymer solution case, it increases a little first and decreases later. For two-phase, cases, peak value will reduce directly in both polymer and water case with the addition of bubbles. The decreasing ratio of pure water case is higher than polymer soution at the initial stage. With the development of mixing layer, there’s no significant influence caused by bubble disturbance.

![Fig. 8 Peak value of average vorticity on each cross-section](image)

4. CONCLUSIONS

An experimental study of gas-liquid two-phase flows of mixing layer with/without polymer additives through a vertical channel had been conducted and compared with pure water mixing layer. It shows clearly that the dynamic development of mixing layer is great influenced by the injection of bubble. When bubbles are injected into pure water or polymer solution, the formation of vortex structures are hindered because of the bubbles distribution. Similar with single phase, the Reynolds stress and vorticity still concentrate in a coniform area of central part of mixing layer. There are some differences that mean Reynolds stress value will decrease with bubble injection and the reduction of Reynolds stress with polymer additives is much more than water. Peak value of average vorticity on each cross-
secton increases first and decreases later for single-phase polymer solution, but decreases directly in both polymer solution and pure water with the injection of bubbles.

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