Experimental investigation of turbulence characteristics in stirred tank with polymer as drag reducing agent using particle image velocimetry

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Abstract. The effect of polymer concentration on turbulence flow field was analyzed by particle image velocimetry inside a stirred tank. With the increment of polymer concentration, the velocity gradient in the radial direction increased and the TKE and EDR rapidly decreased in the impeller region, while the velocity gradient decreased in the axial direction and the TKE and EDR first increased and then decreased in the region close to the wall. Higher polymer concentration resulted in lower turbulence intensity both in the radial and axial velocity components attributing to the weakened and restrained fluctuation intensity of the long-chain in the drag reducer polymer.

1. Introduction
In recent years, with the increase of the scale of the oil pipeline network and the demand for oil products, the method of injecting DRPs to reduce the energy loss has been increasingly used in pipelines. The investigation of turbulence characteristics in drag-reducer flow is critical for understanding the turbulence drag reduction (DR) mechanism [1-3]. This study systematically investigated the influence of DRPs on the turbulence characteristics using PIV, and the turbulent characteristics were analyzed with regard to the velocity field distribution, turbulence intensity, TKE, and EDR obtained at different polymer concentrations.

2. Experimental section
2.1. Materials
The drag reducer used in this study was olefin polymers produced by Conoco Philips (commercially known as Liquid PowerTM, LP, viscosity 194 mPa s, density 970 kg/m3), and was provided as the serous fluid. To obtain clear data from the laser induced plane, Exxsol D130 oil, with low aromatic content and colorless, viscosity 5.0 mPa s, density 824 kg/m3, refractive index 1.45, was used as the oil phase.
2.2. Experimental apparatus
The experiments were conducted in a stirred tank. This stirred tank was a flat-bottomed beaker constructed from borosilicate glass with width $T=150$ mm and height $H=150$ mm, equipped with a four pitched-blade impeller with a diameter $D=50$ mm, width of 10 mm, and height of 5.0 mm, as shown in figure 1[4], and the details of the PIV system arrangement and the measurement procedure have been described by Liu et al [5]. During the experiment, the impeller was placed 50 mm above the bottom with a rotation speed of 700 rpm, and the angle between the impeller blade and the measuring plane was set to $0^\circ$.

![Figure 1. Schematic map of stirred tank geometry and PIV system [4].](image)

3. Results and Discussion
The drag reducer effect on the average velocity field distribution, turbulence fluctuation intensity, TKE, and EDR at different polymer concentrations are presented and discussed, respectively. Here, $U$ and $V$ represent the average velocity in the radial and axial direction, respectively. The origin of the coordinates is located at the center of the tank bottom, and the radial and axial coordinates are normalized with respect to the tank diameter and tank height, which are expressed as $r/T$ and $z/H$, respectively.

3.1. Effect of drag reducing agent on velocity field
The fluid containing polymer drag reducer was measured using PIV under the different polymer concentrations of 0 ppm, 10 ppm, 20 ppm, and 30 ppm. The comparisons of the mean radial and axial velocity profiles with different polymer concentrations at different axial positions (below and above the impeller, that is, $z=46$ and 57 mm) are shown in figure 2.

By comparing figure 2(a) and (c), it can be seen that, in the region below the impeller (figure 2(a)), the highest mean radial velocity occurred close to the impeller ($0< r/Gird <10$) and increased from 0.37 to 0.53. In the region above the impeller (figure 2(c)), the highest mean radial velocity occurred far from the impeller ($20< r/Gird <30$) and also increased from 0.21 to 0.32. The velocity gradient of the drag-reduced flow in the radial direction of the region below and above the impeller increased when the polymer concentration increased from 0 ppm to 30 ppm. In other words, the flow in the radial direction approached the laminar flow velocity as the viscous substrate layer became thicker [6].

However, the velocity gradient of the drag-reduced flow in the axial direction decreased when the polymer concentration increased from 0 ppm to 30 ppm, as shown in figure 2(b) and (d), owing to the weakening of the axial disturbance. By comparing figure 2(b) and (d), it can be seen that the highest mean axial velocity occurred close to the impeller ($0< r/Gird <10$), in the region below the impeller.
(figure 2(b)). In the region above the impeller (figure 2(d)), the highest mean axial velocity occurred far from the impeller ($20 < r/Gird < 30$), similar to the radial velocity distribution.

![Image](figure 2(a). Mean radial (a and c) and axial (b and d) velocity distribution with different polymer concentrations at different axial positions: (a and b) $z=46$ mm and (c and d) $z=57$ mm.)

3.2. Effect of drag reducing agent on turbulence fluctuation intensity

The turbulence fluctuation intensity is also called turbulent intensity, and represents the range of change in the velocity. By comparing figure 3(a) and (d), it can be seen that the region with the higher turbulent intensity was generally around the impeller, and the turbulent intensity decreased when the polymer concentration increased from 0 to 30 ppm, particularly in the region around the impeller. This indicates that the compensation for the turbulent intensity in the mainstream direction was reduced by 50% for the turbulent drag-reducing flows with the same flow rate.

As in the radial direction, the turbulent intensity distribution in the axial direction also decreased as the polymer concentration increased from 0 ppm to 30 ppm, particularly in the region close to the impeller, as can be seen by comparing figure 4(a) to (d).

In accordance with the contour map shown in figure 3 and 4, it is clear that the turbulent intensity distribution of the pure oil system in the impeller region was higher than that in the drag-reducing flows. In other words, the long-chain of the drag reducer polymer weakened and restrained the fluctuation intensity, particularly in the tangential direction, and promoted the mainstream flow. This also explains why the drag reducer polymer does not work with laminar flow, seeing as the laminar flow is a stratified flow along the mainstream direction without tangential fluctuations. Additionally, by combining figure 2 to 4, it can be seen that the addition of drag reducer polymer (DRP) changed the turbulent flow, which became more similar to laminar flow.
Figure 3. Turbulent intensity distribution of radial velocity component $T(u)$ at (a) 0 ppm; (b) 10 ppm; (c) 20 ppm; (d) 30 ppm.

Figure 4. Turbulent intensity distribution of axial velocity component $T(V)$ at (a) 0 ppm; (b) 10 ppm; (c) 20 ppm; (d) 30 ppm.
As shown in figure 5, this was a purely physical process. Before the addition of DRP, the fluid particle in the axial direction moved forward at a faster velocity. As the fluid moved faster relative to the pipe wall, the influence of the small disturbance also became greater, and the large scale vortex easily broke by small-scale eddies owing to the fluctuation and vortex caused by random motion in the radial and tangential directions. Finally, the small scale eddies weakened and diminished under the effect of viscous friction, which converted some kinetic energy into heat energy and dissipated it. This was particularly severe in the near-wall region, owing to its relatively larger shear stress and viscous force. After the addition of DRP, the velocity gradient increased and the long chain of the polymer drag reducer unfolded along the axial direction. If a fluctuating flow existed, it would have been affected by the long chain of the polymer drag reducer and would convert its kinetic energy into elastic potential energy and store it. Thus, the energy loss of the flow was reduced, which indicates that the friction resistance decreased along the pipe.

![Figure 5. Schematic of fluid particles in turbulent flow before and after addition of DRP.](image)

### 3.3. Effect of drag reducing agent on TKE

The distribution of TKE with different polymer concentrations is shown in figure 6. By comparing figure 6(a) to (d), it can be seen that, in the impeller region, the TKE (red color) decreased as the polymer concentration increased from 0 ppm to 30 ppm. However, in the region close to the wall, the flow area (green color) representing the fluid with flow ability also slightly increased when the polymer concentration increased from 0 ppm to 10 ppm, and then decreased when the polymer concentration further increased to 30 ppm.

After adding DRP in the turbulent flow, the long chain of the polymer drag reducer affected the disturbance in the radial and axial directions, and converted the kinetic energy into elastic potential energy. This weakened and inhibited the radial and axial pulsation and vortex, reduced their interference with the mainstream flow, and promoted the mainstream flow while reducing the axial pulsation. This also explains why the addition of polymer drag reducer did not produce a drag-reducing effect in the laminar flow, which is a stratified flow along the mainstream direction, without axial pulsation.

![Diagram showing TKE distribution with and without DRP](image)
3.4. Effect of drag reducing agent on EDR

Figure 7 shows the EDR distribution with different polymer concentrations. It was found that the region with higher EDR was mainly the region close to the impeller. In the impeller region, the area of maximum EDR (red color) sharply decreased as the polymer concentration increased from 0 ppm to 30 ppm. However, in the region close to the wall, the flow area (green color) representing the fluid with flow ability increased when the polymer concentration increased from 0 ppm to 10 ppm, and then decreased when the polymer concentration became higher than 10 ppm, as did the TKE. This occurred because the interaction between the long chain of the polymer drag reducer and the turbulence fluid elements inhibited the generation of turbulence pulsation or a vortex, reduced the pulsation intensity, and thus reduced the energy loss.

4. Conclusions
1. The velocity gradient of the drag-reduced flow in the radial direction increased, but the velocity gradient of the drag-reduced flow in the axial direction decreased as the polymer concentration increased from 0 ppm to 30 ppm.
2. The influence of the polymer drag reducer on the turbulence intensity suggests that higher polymer concentration results in lower turbulence intensity, which is attributed to the weakening and restraining of the fluctuation intensity of the long-chain in the drag reducer polymer.

3. As the polymer concentration increased, the TKE and EDR rapidly decreased in the impeller region, while first increased and then decreased in the near-wall region, for the long chain of the polymer drag reducer weakened the turbulence pulsation by converting its kinetic energy into elastic potential energy.

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