Statistical Investigation on Coherent Vortex Structure in Turbulent Drag Reducing Channel Flow with Blown Polymer Solution

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Abstract. Coherent vortex structure in turbulent drag-reducing channel flow with blown polymer solution from the wall was investigated. As a statistical analysis, we carried out Galilean decomposition, swirling strength and linear stochastic estimation of the PIV data obtained by the PIV measurement in $x-y$ plane. Reynolds number based on bulk velocity and channel height was set to 40000. As a result, the angle of shear layer that cleared up by using Galilean decomposition becomes small in the drag-reducing flow. Q3 events were observed near the shear layer. In addition, as a result of linear stochastic estimation (LSE) based on swirling strength, we confirmed that the velocity under the vortex core is strong in the water flow. This result shows Q2 (ejection) are dominant in the water flow. However, in the drag-reducing flow with blown polymer solution, the velocity above the vortex core become strong, that is, Q4 (sweep) events are relatively strong around the vortex core. This is the result of Q4 events to come from the channel center region because the polymer solution does not exist in this region. The typical structure like this was observed in the drag-reducing flow with blown polymer solution from the wall.

1. Introduction

Addition of dilute polymer solution to turbulent wall-bounded flow can cause significant reduction in the skin friction drag. This phenomenon is called as \textit{Toms effect}, since it was discovered by Toms (1948). After this finding, many researchers have been investigated the drag-reducing effect of added polymer to turbulent flow.

The most typical study of the drag-reducing flow is about that by the polymer homogeneous solution (Warholic et al. 1999 and White et al. 2004) Warholic et al. classified the drag-reducing flow into two cases on the basis of the drag reduction rate (DR). One is the case that DR is less than 35\% (SDR: small drag reduction), the other is that DR is more than 35\% (LDR: large drag reduction). In the case of the SDR, characteristics of the results are that the mean velocity profile is displaced upward and has the same gradient as the log-law profile, and Reynolds shear stress deceases with increasing drag reduction rate. Moreover, the polymer stress which is firstly reported by Willmarth et al. (1987) increases in the near-wall region. The polymer stress is defined as the stress deficit in the drag-reducing flow, and related to the mechanism of the
drag reduction. In the numerical study, this polymer stress is represented as the viscoelastic stress. In contrast, in the case of the large drag reduction, the mean velocity gradient increases with increasing drag reduction rate, and velocity profile is displaced upward toward the Virk’s asymptote (Virk 1975). In addition, Reynolds shear stress largely decreases, and the polymer stress increases with increasing drag reduction rate in entire region.

In the numerical simulation, there were several studies for the drag-reducing flow using various models such as Giesekus model, Finitely Extensible Nonlinear Elastic with the Peterlin approximation (FENE-P) model (Dubief et al. 2004) and dumbbell model. Tsukahara et al. (2010) carried out a DNS study of drag reducing-flow using the Giesekus model for surfactant solution and investigated the relation between Weissenberg number and drag reduction. According to their calculations, high drag reduction can be achieved by suppressing the production of turbulence for high Weissenberg number. In addition, this study can lead to understand the spatial vortex structure which can not be observed from experimental study.

According to above knowledge, drag reduction occurs by inhibiting the near-wall ejections. On the basis of this knowledge, we suggested the Wall Blowing method which is the method for providing polymer solution in only the near-wall region by oozing polymer solution from the porous wall. Therefore, we supposed that this method can inhibit the Q2 events only near the wall. In our previous study (Ishitsuka et al. 2010), we reported that Reynolds shear stress decreases with drag reduction in the near-wall region. However, there is not enough knowledge about the spatial vortex structure which leads to drag reduction flow with blown polymer solution. Therefore, objective of this study is to analyze the PIV results statistically with Galilean decomposition, swirling strength and investigate the relationships between the coherent vortex and Reynolds shear stress.

2. Experimental set-up

2.1. Flow system

The experiments were performed with a closed-circuit water loop having a two dimensional channel with a blowing wall as shown in figure 1. This channel was made of transparent acrylic resin, with a length of 6000 mm, a width of 500 mm, and a height of 40 mm ($2h$). To measure the flow rate ($Q$), an electromagnetic flow meter with an uncertainty of ± 0.01 m$^3$/min was installed upstream of the channel. A storage tank in the flow loop was equipped with a heater and an agitator in order to adjust the fluid temperature, which was stabled at 25°C with an uncertainty of ± 0.1°C during the experiment.

![Figure 1. Experimental facilities.](image)

### Table 1. Flow conditions.

|                | Water | Blown polymer solution |
|----------------|-------|------------------------|
| $Re_b$         | 40000 | 40000                  |
| $C_0$ (ppm)    | 0     | 100                    |
| $Re_f$         | 804   | 750                    |
| $U_{blow}$ (m/s) | 0  | $5.9 \times 10^{-5}$  |
| $U_{bulk}$ (m/s) | 0.88 | 0.88                  |
| DR (%)         | 0     | 16.3                   |
2.2. Blowing system
The wall for blowing polymer solution was made of sintered porous metal, having 450 mm × 1350 mm in size. The pore size of the blowing wall was 2 μm. This blowing wall was attached to one side of the channel with its leading edge located 2300 mm downstream from the entrance of the channel. The blowing rate of the polymer solution could be adjusted by the pump and flow meter, and the polymer solution could be blown from whole surface of the blowing wall.

2.3. Polymer solution
The polymer used in this experiment was PEO-18Z produced by Sumitomo Seika Chemicals Co., LTD. Major component of this polymer was an water-soluble Poly(ethylene oxide) having 4.3 million of molecular weight. Weight concentration of the polymer solution was prepared 100 ppm and the blowing rate of the polymer solution was fixed at 2.0 L/min from whole surface of the blowing wall. In this condition, the blowing velocity was 5.9×10⁻⁵, and the ratio of the blowing velocity to the bulk velocity was 6.7×10⁻⁵. Therefore, it seems that the streamwise channel flow is not affected by the blowing method.

2.4. DR measurements
The wall shear stress was estimated by the static pressure gradient, which could be measured by the pressure taps attached to the opposite side of the blowing wall over a distance of 1.65 m. However, it is necessary to estimate the net wall shear stress upon the blowing wall, because the blowing wall was attached to one side of the channel and polymer solution was is blown from the only this blowing wall. Therefore, we supposed that the wall shear stress upon the opposite side wall of the blowing wall was the same as the water flow, and the net wall shear stress upon the blowing wall was calculated by the following equation:

\[ \tau_{\text{blowing}} = 2 \cdot \frac{h}{L} \Delta p - \tau_{\text{water}} \]  

where \( \tau_{\text{blowing}} \) and \( \tau_{\text{water}} \) are the wall shear stress with and without blown poloymer solution at the same Reynolds number, respectively. In the experiment, the drag reduction rate was defined as follows:

\[ DR(\%) = \frac{\tau_{\text{water}} - \tau_{\text{blowing}}}{\tau_{\text{water}}} \times 100 \]  

Table 1 lists the drag reduction rate with polymer solution blown. We obtained 16.3% drag reduction by the blown polymer solution.

2.5. PIV measurement
The PIV system consists of a double-pulse laser, laser sheet optics, CCD camera with a resolution of 2048×2048 pixels, synchronizer and computer with image-processing software (Dantec Dynamics, Dynamics studio ver. 2.30). The double-pulsed laser (New wave Research Co., Ltd., Minilase- II/30Hz) was a combination of a pair of Nd-YAG lasers, each having an output of 30 mJ/pulse and a wavelength of 532 nm. Laser sheet thickness was set to 0.6 mm. The synchronization device, which generates pulses to control the double-pulse laser, communicated with the CCD camera and the computer. The PIV images were analyzed using a cross-correlation technique. The interrogation area was set to 64×64 pixel with a cross-correlation. Each interrogation area was overlapped by 75%.

We used this PIV system to measure the instantaneous velocity \( u - v \) in the \( x - y \) plane. Turbulent statistics were calculated by 62500 vectors (125 vectors at each \( y \)-position in one velocity field × 500 velocity fields). The flow was seeded by nylon particles as the tracer. These particles have 4.1 μm in mean diameter and 1.02 with a specific gravity to the water. Therefore, the tracer particles were enough to follow the flow faithfully.
3. Analytical methods

3.1. Galilean decomposition
Galilean decomposition is the technique that visualized uniform momentum zone in instantaneous velocity fields suggested by Adrian et al. (2000). This method deduced arbitrary velocity from the original velocity fields as following equation;

\[ U_c = u - \alpha U_b \]  \hspace{1cm} (3)

where \( U_c, u, \alpha \) and \( U_b \) are the processing velocity by Galilean decomposition, original velocity, proportional constant and bulk velocity, respectively. The proportional constant is defined arbitrary value in the range from 0.5 to 1. Adrian et al. (2000) suggested that \( \alpha \) is larger and larger (close to 1), become visible structures in the outer region. That is, the large scale structure can be visible by having a larger value.

3.2. Swirling strength
As one of the visualized vortex in the flow fields, vorticity is a useful method. However, vorticity includes rotation and shear, and it is necessary to extract the vortex deducting shear. Swirling strength is an effective method which identified only vortex core. The local velocity gradient tensor represents the turbulent motion including shear and rotation. Since PIV data, gets two dimensional velocity components, all direction of the velocity component cannot get at one time. However, the local velocity gradient tensor in two dimensional can be computed in PIV data, as following equation;

\[ D_{ij} = \frac{\partial u_i}{\partial u_j} \]  \hspace{1cm} (4)

where \( i,j=1,2 \) are the streamwise and wall-normal directions, respectively. In this case, the local velocity gradient tensor has a pair complex conjugate eigenvalue. Therefore, vortex core extracts by plotting iso-surface of \( \lambda_{ii} > 0 \).

3.3. Linear Stochastic Estimation (LSE)
In turbulence, the velocity correlation relates to the scale and structure of vortex. Using this property, Adrian et al. (1994) developed the Linear Stochastic Estimation (LSE). This method is effective to extract arbitrary turbulent structure in the flow fields. The conditional average fields in an event \( (E) \), as shows following equation,

\[ < u_i(x') \mid E > = L_{ij} (x') E_j (x) \]  \hspace{1cm} (5)

where \( L_{ij} \) is correlation-tensor which is determined by minimizing the mean-square error between the estimate and the conditional average. Adrian (1994) reported that hairpin vortex was extracted around the Q2 events in isotropic turbulence with LSE method, and it indicated utility to use the LSE method. There is arbitrary property to the extracting structure, but this method can apply to clear up hidden structure in the turbulence.

4. Results and Discussion

4.1. Instantaneous velocity fields
Figure 2 shows the instantaneous velocity fields analyzed by (a) the Galilean decomposition, (b) the swirling strength and (c) Reynolds shear stress normalized by the frictional velocity for the water flow. As shown in figure 2(a), the velocity map was viewed in a frame of reference convecting by \( \alpha = 0.8 \). This figure indicated that a uniform momentum zone of low speed fluids can be seen over the near-wall region till \( y^+ = 400 \). According to Adrian et al. (2000), the
$U_c = u - 0.8U_b$

Figure 2. Various analysis in water flow: (a) Galilean decomposition, (b) swirling strength, (c) Reynolds shear stress normalized by the frictional velocity.
$U_c = u - 0.8 U_b$

Figure 3. Various analysis in drag reducing flow: (a) Galilean decomposition, (b) swirling strength, (c) Reynolds shear stress normalized by the frictional velocity.
individual group of the hairpin vortex in the same streamwise velocity is called hairpin vortex packet and the velocity difference exists between each packets. The boundary on this velocity difference is called shear layer which is represented by the white-broken line in figures 1 and 2. As a proof of this, the spanwise vortices which correspond to head of the hairpin vortex can be seen on the shear layer by the analysis of the swirling strength as shown in figure 2(b). These vortex heads are denoted by A and B. In addition, the vectors, which are expressed the instantaneous velocity, are large under the vortex core extracted by the swirling strength.

Moreover, figure 2(c) indicates that strong Reynolds shear stress exists under the vortex cores. Therefore, Reynolds shear stress is produced under the head of hairpin vortex and this fact agrees with the suggestion by Adrian et al. (2000). According to the Adrian model, the Q2 event (ejection), which is the moving-up motions of low-speed fluids from the wall, occurs under the hairpin head and the transition from a Q2 to a Q4 from the outer region event correspond to VITA event that is expressed inclined shear layer in figure 2(a). Above vortex characteristics, Reynolds shear stress produced in turbulence.

In contrast, Figures 3 (a)-(c) shows the same as figure 2 for the drag-reducing flow with polymer solution blown. As shown in figure 3(a), the inclination angle of the shear layer is small compared to the water flow represented by the white broken line. This result indicates that Q2 event in the near-wall region is suppressed by the blown polymer solution. However, the vortex core also exists near the inclined shear layer same as the water flow denoted C as shown in figure 3(b). The characteristic structure in the drag-reducing flow with blown polymer solution is that the interaction motions denoted D are observed in the near-wall region. These interaction motions are Q3 events and can be confirmed under the shear layer (see figure 3(c)). This existence of the interaction motions related to the drag reduction was alluded in our previous study (Ishitsuka, 2011) by the quadrant analysis. Moreover, Q2 event in the near-wall region is suppressed because the polymer solution exists only near the wall, but Q4 event from the outer region remains unaffected by polymer in order that the polymer solution does note exist in the outer region. As a result, the strength of Q4 event becomes relatively large compared with Q2 event and the inclination angle of the shear layer to the streamwise direction decreases due to the influence of strong Q4 event. And the angle of inclined shear layer is low due to the influence of becoming strong Q4 event. This characteristic behavior (i.e. decrease of Q2 event and increase of Q3 event) leads to decrease of the Reynolds shear stress. Finally, we summarized the characteristic structure of the drag-reducing flow with blown polymer solution as follows; (a) Q2 event (ejection) is suppressed but Q4 event (sweep) is not affected, (b) Q3 event appears under the shear layer, and (c) the inclination angle of the shear layer becomes small.

4.2. Vortex core

We defined the shape of average swirling strength by using correlation coefficient as follows;

$$R_{\lambda\lambda} = \frac{\langle \lambda_{\alpha}(x)\lambda_{\alpha}(x') \rangle}{\langle \sigma_{\alpha}(x)\sigma_{\alpha}(x') \rangle}$$

(6)

where $\sigma$ refers to the root-mean square of the given quantity and the operator $\langle \cdot \rangle$ denotes the ensemble average. Figure 4 shows contour line of the correlation coefficient of swirling strength and the vector fields for (a) water flow and (b) with blowing polymer solution from the channel wall. The calculation was executed at $y^+ \approx 200$ because the typical flow structure was observed around here. In these figures, the velocity vector fields shown in the background of the correlation coefficient of swirling strength represents the conditional averaged velocity around the swirling strength estimated by using LSE as following;

$$\langle u'_j(x') | \lambda_{\alpha}(x) \rangle \approx \frac{\lambda_{\alpha}(x)u'_j(x')}{\lambda_{\alpha}(x)} \frac{\lambda_{\alpha}(x)}{\lambda_{\alpha}(x)}$$

(7)
Figure 4. Correlation coefficient of swirling strength and vector field estimated LSE: (a) Water flow, (b) Blown polymer solution.

where the rotational direction is clockwise which discriminates the term of vorticity. These velocity vectors are normalized by the frictional velocity. Furthermore, the length of these velocity vectors is shown in figure 5 by the contour. In the water flow as shown in figures 4(a) and 5(a), turbulence motions are intense under the swirling strength, that is, the strong Q2 event is observed around the vortex core. This means that the swirling strength which is corresponding to the head of hairpin vortex, contributes to production of the Reynolds shear stress. Since our statistical analyses on the water flow corresponds to those by Adrian et al., we judged that our analyses are adequate.

In contrast, in the case of the drag-reducing flow with blown polymer solution as shown in figures 4(b) and 5(b), vortex shape strains in an oblique direction. This result indicates that shearing force becomes strong by addition of the polymer solution and hairpin vortex is strained. In addition, focusing on the velocity fields, turbulent motions under the vortex core are suppressed but above vortex core are intense. These turbulent motions can be seen more clearly by the contour of the vector length as shown in figure 5(b). These results show that Q2 event in the near-wall region are inhibited by blown polymer solution and high-speed fluid motions such as outward interaction and sweep coming from channel center where the polymer solution does not exist, become remarkable. Xu et al. (2011) carried out PIV measurement in $x-z$ plane and reported that near-wall streaks strain by blown polymer solution, and these streaks develop to the channel center with remaining strain. Considering this strain of the streaks, head of hairpin vortex strains in the region away from the wall. This characteristic coherent structure is specific to drag reducing flow with blown polymer solution from the channel wall.

5. Discussion of the characteristic turbulent structure

In this chapter, we suggest the model of the characteristic turbulent structure including hairpin vortex in the drag-reducing flow with blown polymer solution from the wall as illustrated in figures 6 (a) and (b). In the Newtonian fluid flow as shown Figure 6 (a), Adrian et al. (2000) reported that the packet of the hairpin vortex which is lined near the shear layer develops toward the wall-normal direction because Q2 event is dominant in the near-wall region. When the packet reaches at a certain height, the fluid goes on busting $\overline{u}$, and Reynolds shear stress is produced. The turbulence can be maintained by repeating this process, and the flow becomes instability away from the wall.

In contrast, the turbulence stabilizes in entire region by acting the polymer in the Non-
Newtonian fluid flow such as the drag-reducing flow by the homogeneous polymer solution (Warholic et al. 1999). In other word, the flow changes to laminar-like, and the production of Reynolds shear stress is suppressed. As a result, large drag reduction effect occurs in homogenous polymer solution flow. In the present study case for the wall blowing method, the polymer exists only in the near-wall region. Thus, polymer act to stabilize the turbulence in only the near-wall region, and the Q2 and Q4 events in near-wall region are suppressed by the polymer. As a result, development of the turbulence toward the wall-normal direction is suppressed, and low momentum fluid having a packet of hairpin vortex stay near the wall. However, Q4 events are not suppressed away from the wall since the polymer does not exist in this region. Therefore, this peculiar turbulent structure appears in the drag-reducing flow with blown polymer solution from the wall.

6. Conclusion

In this work, we compared the spatial structures of the water flow and the drag-reducing flow with blown polymer solution from the channel wall. Following results were obtained in this study. The angle of shear layer decreases with drag reduction and Q2 event near the shear layer were suppressed. Instead of this, we observed Q3 motions in the near-wall region with drag reduction. These event contribute to decrease of Reynolds shear stress.

Moreover, we conducted linear stochastic estimation based on swirling strength to clear up velocity fields around the vortex core. In the water flow, velocity under the vortex core is strong, and this trend shows Q2 event which produces Reynolds shear stress are dominant. In contrast, velocity above the core become strong in the drag-reducing flow with blown polymer solution, that is, Q4 event coming from channel center are dominant because the polymer exists in only the near-wall region.

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Figure 6. Conceptual model compared to water Newtonian and non-newtonian: (a) water flow, (b) blown polymer solution.

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