Characteristics of Low-Speed Streaks in the Flow of Drag-Reducing Surfactant Solution*

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The characteristics of low-speed streaks in the turbulent channel flow of a drag-reducing surfactant solution are studied by employing the hydrogen-bubble flow visualization method. The mean velocity profiles and the distributions of streamwise turbulence intensity are also obtained. It is shown that, at a large drag reduction rate \( \text{DR} \), the profile of the streamwise turbulence intensity has a plateau region around its peak. In the drag-reducing flow, the mean spanwise streak spacing reaches minimum at some distance from the wall. In the drag-reducing flow of high-density (1 000 ppm) surfactant solution, the low-speed streaks appear intermittently at the Reynolds number smaller than those for the 'hump' of the \( f-Re \) curve \((f: \text{friction factor})\). The mean spanwise streak spacing very near the wall increases as \( \text{DR} \) becomes large. It is speculated that the nondimensional wall-normal distance \( y' \) of the center of streamwise vortices is larger for the flow of large \( \text{DR} \) compared with that for the Newtonian fluid flow.

**Key Words:** Turbulent Flow, Non-Newtonian Fluid, Flow Visualization, Velocity Profile, Drag Reduction, Surfactant Solution, Low-Speed Streak

1. Introduction

In wall turbulence, there exists a coherent structure (spatial structure of low-speed sublayer streaks) that a low-speed region and a high-speed region both long in the streamwise direction are situated side by side. A series of events, called bursting, i.e., the rising, vibrating, and collapse of a low-speed region (low-speed streak), is closely related with turbulence production and turbulent momentum transport. In the flow of dilute polymer solutions which show a remarkable drag reduction in turbulent flow\(^{33}\), it is reported that the averaged spanwise spacing of the low-speed streaks increases and the mean period between the bursts grows longer as the drag reduction rate increases. Similar behavior is expected for a flow of drag-reducing surfactant solution, but the mechanism of the drag reduction of the surfactant solution is assumed to be different from that of dilute polymer solutions\(^{33}\), and the streak structure may be different.

In the present study, two-dimensional turbulent channel flow of drag-reducing surfactant solution is investigated by employing the hydrogen-bubble flow visualization method, and the behavior of streak structure with the increasing drag reduction rate is clarified. Moreover, the results obtained here are compared and discussed with the data for dilute polymer solutions.

2. Nomenclature

\( \text{DR} \) : percent drag reduction
\( f \) : friction factor
\( H \) : channel width
\( m \) : hydraulic radius
\( Re \) : Reynolds number \((=4mU/\nu)\)
\( U \) : time-mean velocity in the cross section
\( u' \) : streamwise fluctuating velocity component
\( u_c \) : friction velocity

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$y$ : wall-normal distance
$\lambda$ : spanwise spacing of low-speed streak
$\eta$ : shear viscosity
$\nu$ : kinematic viscosity

Superscript

$()$ : ensemble average or time-mean value
$(\cdot)^+ : $ nondimensional value in terms of $u_r$ and $\nu$

3. Experimental Apparatus and Procedure

The experimental apparatus of two-dimensional channel flow is the same with the one used before\textsuperscript{[59].} Two-dimensional channel is made of acrylic plates and the dimensions are the width $H=40$ mm, the height $B=400$ mm, the length $L=4$ m. The pressure drops are measured from static pressure tappings situated at $55H \approx 80H$ downstream from the channel inlet. Figure 1 shows the details of the measuring section using the hydrogen-bubble flow visualization method. A 25-μm-diameter stainless wire was used to generate hydrogen-bubbles and was arranged in spanwise direction at $70H$ downstream from the inlet. A DC pulse generator (Sugawara Lab. Inc. MN-305) was used to generate hydrogen-bubbles, and the hydrogen-bubble time-lines were viewed and recorded using a CCD video camera (Sony AVC-D7) and a VTR (National NV-8550). The individual video frames are converted to a digital array using an image-processing system (Technical support DIG98) and then analyzed by a microcomputer. The surfactant system used here consisted of equimolar mixtures of n-tetradecyltrimethylammonium bromide with sodium salicylate, which were added to the pure water that removed ions and impurities from tap water by a water purifier and a 5 μm filter. The concentrations of the mixture used here are 500 ppm and 1 000 ppm by weight.

Figure 2 shows a plot of the shear viscosity $\eta$ versus the shear rate at the wall $\gamma_w$ for the 1 000 ppm surfactant solution measured by a capillary viscometer. As described before\textsuperscript{[59]}, if the surfactant system contains rod-like micelles and the shear rate exceeds a critical value, the micelles coalesce into a huge structure and the shear viscosity suddenly increases. Such a state of increased viscosity is called a shear-induced state, SIS, which can be seen clearly in Fig. 2. Compared with the data for the 400 ppm solution shown in the previous paper, the viscosity at the low shear rate increases, and the sudden increase in the viscosity due to the formation of SIS becomes more remarkable as the concentration increases. In the following, the constant shear viscosity $\eta$ at the low shear rate where SIS is not formed was used as in the previous paper.

4. Experimental Results and Discussion

4.1 Pressure drop

Friction factors versus Reynolds number are shown in Fig. 3 for a 1 000 ppm surfactant solution at various fluid temperatures. Shown by the solid lines in this figure are the laminar theoretical value

$$4f=1.313 \times 64/Re$$

(1)

and Blasius's equation for Newtonian turbulent flow.

![Fig. 2 Shear viscosity of a surfactant solution](image)

![Fig. 3 Friction factor of 1 000 ppm solution](image)
\[ f = 0.316 \frac{4Re^{-0.25}}{f_w} \]  
\( f \) along with the maximum drag reduction asymptote for polymers which was found empirically by Virk \(^{(1)}\):

\[ \frac{1}{\sqrt{f}} = 9.5 \log \left( \frac{Re}{f} \right) - 19.06 \]

The friction factor \( f \) for the surfactant solution in the turbulent flow region shows strong temperature dependence, i.e., drag reduction becomes less remarkable with the temperature increase. This may be caused by the fact that the length of the rod-like micelle in the solution becomes shorter with the fluid temperature increase \(^{(4)}\), as mentioned in the previous paper \(^{(3)}\).

In this study using the hydrogen-bubble flow visualization method, a decrease in the effectiveness of drag reduction was found as shown in Fig. 4, depending on the cumulative working time of the pulse generator for hydrogen-bubble generation. (In this figure, the working time of the pulse generator is shown in parentheses.) The fact that the drag reduction effect decreases with increasing working time may be due to the decrease in the Br \(^{-}\) ion by the electrolysis and shortening of the rod-like micelle \(^{(4)}\). At the fluid temperature and the concentration shown in Fig. 4, the value of the friction factor \( f \) remained unchanged when the working time exceeded 3.5 hours. In this condition, the drag reduction effect still exists, so it does not disappear completely due to the electrolysis of the solution.

In the experiment using the hydrogen-bubble method shown below, the working time of the pulse generator at each Reynolds number was limited to a short period (within 10 minutes), which hardly causes the decrease in the drag reduction rate by the electrolysis of the solution.

The drag reduction rate is defined by the following equation, and Fig. 5 shows the data of Fig. 4 replotted in \( DR-Re \) coordinate.

\[ DR = \frac{f_{w} - f}{f_{w}} \times 100 \text{ (\%)} \]

Here, \( f_{w} \) is the friction factor for water and \( f \) that for surfactant solution. The maximum 77% drag reduction rate can be seen from Fig. 5. It can also be seen that \( DR \) decreases once in the region \( Re = 10,000 \sim 15,000 \) with an increase in \( Re \), except for the data with the working time of 3.5 hours. This phenomenon corresponds to the 'hump' portion of the \( f-Re \) curve in Fig. 4. According to Ohlendorf et al. \(^{(1)}\), such a phenomenon appears when the mean shear rate in the buffer region exceeds a critical value at which SIS takes place. In the striae structure near the wall described below, it is found that the flow pattern resembles one in the transition region from laminar to turbulent when \( Re \) is less than for the 'hump' of the \( f-Re \) curve.

### 4.2 Mean velocity profile and distribution of turbulence intensity

The flow velocity was measured from the displacement of hydrogen-bubble time-lines generated from the wire by the charge of pulse voltage at a constant time interval \(^{(2)}\), i.e., the mean velocity during the time \( \Delta t \) was approximated as dividing the time-line displacement \( \Delta x \) between the two bubble timelines nearest the generating wire by the pulse time interval \( \Delta t \). In this study, \( \Delta t \) was chosen from among 3 intervals; 1/30, 2/30, and 3/30 seconds, according to the flow velocity, and the image sampling was also set up in accordance with this. As for the influence of the wake of the bubble-generating wire, it was examined beforehand in various working fluid by using the rotating tank for the calibration of the hot film probe \(^{(2)}\). Referring to these results, the above-mentioned velocity \( \Delta x/\Delta t \) was calibrated. Time-mean values of the velocity \( \bar{u} \) and turbulence intensity \( u_{rms} \) shown below were calculated from 256 time series data of the velocity obtained at each measuring point in the manner mentioned above. It was confirmed that there was no difference in the results even when twice the data (512 data) were used for calculation.

Figure 6(a) and (b) show the mean velocity profiles in the logarithmic scale, where a nondimensional velocity \( \bar{U} = \bar{u}/u_{t} \) and a nondimensional wall
distance $y^+ = y \nu / U'_e$ are used. Here $U'_e$ is the friction velocity. When the water was used, the friction velocity was calculated from the logarithmic velocity distribution ($U^+ = 5.75 \log y^+ + 5.5$), which has been well established for a Newtonian fluid flow. For the surfactant solution, the friction velocity was obtained from the result of pressure drop measurement, since the universal velocity profile is not established yet.

The mean velocity profile for the 1000 ppm surfactant solution is shown in Fig. 6(a) and for the 500 ppm solution in Fig. 6(b) in comparison with that for water. It is found from these figures that the velocity profile in the log-law region agrees with the ultimate profile suggested by Virk
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$$U^+ = 26.9 \log y^+ - 17 \quad (5)$$

when the drag reduction rate $DR$ for the surfactant solution amounts to $55 - 62\%$. In the case of $DR = 26\%$, the velocity profile in the log-law region shows nearly a straight line parallel to the logarithmic distribution for water flow.

$$U^+ = 5.75 \log y^+ + 5.5 \quad (6)$$

In the previous paper\(^{(5)}\), an S-shaped velocity profile was found when the drag reduction rate was large, and a velocity larger than Virk's ultimate profile was obtained at large $y^+$ values. Such a trend cannot be seen in Fig. 6, presumably because the drag reduction rate in this study is smaller than that for the previous one.

Figure 7 shows the distribution of streamwise turbulence intensity $U'_w$. When water is used, the turbulence intensity measured here shows a slightly larger value than that calculated by Kim et al.\(^{(6)}\) in terms of the direct numerical simulation shown by a solid curve in the figure. This is probably caused by the effect of the bubble-generating wire and the turbulence becomes a little larger. Generally, in the drag-reducing flow, the streamwise turbulence intensity reaches maximum farther from the wall compared with the Newtonian fluid flow, as mentioned in the previous paper\(^{(3)}\). In Fig. 7, it is worth noticing that the peak value of $U'_w/Re^{1/2}$ is much larger than that for water flow, and there is a plateau region around its peak when $DR$ is large. It is also characteristic that in this case the turbulence intensity varies suddenly not only in the vicinity of the wall but also in the large $y^+$ region.

4.3 Streak structure

The measurement of the low-speed streaks using hydrogen-bubble was carried out by Smith et al.\(^{(9)}\) and Iritani et al.\(^{(10)}\) for Newtonian fluid flow. In this study the low-speed streak was detected adopting the definition similar to that used by Iritani et al.; it is detected when a local peak was observed in the
hydrogen–bubble time–line over the specified period \( \Delta t \) (see Fig. 8). The bubble–pulse period was put at suitably in the range of \( 1/60 \sim 1/15 \) seconds according to the measuring condition, while \( \Delta t \) was put at 0.2 second. The video frames were played back in the monitor with the sampling time of \( 1/15 \sim 1/5 \) seconds, and the low–speed streaks detected in the frame were marked in turn on a transparency sheet where the abscissa indicates a time scale. The time evolution of the low-speed streaks obtained in this way are shown in Fig. 9 and 10. In these figures, the abscissa shows time in \( \nu/\nu \) unit and the ordinate spanwise length in \( \nu/\nu \) unit.

The results for water flow are shown in Fig. 9 (a). It is found that the streaks distribute more densely as they approach the wall similar to the results obtained by Smith et al. and Iritani et al. The results for the 500 ppm surfactant solution at \( Re = 10000 \) are shown in Fig. 9(b) and (c), where the drag reduction rate of the former is fairly smaller than that of the latter. As the figures show, the mean spanwise streak spacing in the drag–reducing flow

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**Fig. 8** Definition of low–speed streak

(a) WATER \( Re = 10000 \)

(b) CuTASol 500 ppm \( Re = 10000, DR = 26\% \)

(c) CuTASol 500 ppm \( Re = 10000, DR = 60\% \)

**Fig. 9** Time evolution of low–speed streaks

(a) CuTASol 1000 ppm \( Re = 10000, DR = 55\% \)

(b) CuTASol 1000 ppm \( Re = 20000, DR = 62\% \)

**Fig. 10** Time evolution of low–speed streaks
increases with increasing $DR$. The streak spacing at some distance from the wall is smaller than that in the vicinity of the wall, which differs from the case of water flow.

Figure 10(a) and (b) show the time evolution of low-speed streaks for the 1 000 ppm surfactant solution. At $Re=10 000$, shown in Fig. 10(a), the spanwise streak spacing increases and decreases intermittently, which is similar to the phenomenon observed in water flow in the transition region as shown in Fig. 11. Therefore, it is conjectured that the flow shown in Fig. 10(a) has not become fully turbulent.

From the time evolution of low-speed streaks shown in Fig. 9 and 10, the spanwise streak spacing are measured at every $\Delta t$ time interval, and the results are shown in Fig. 12 in terms of histogram. The solid curve drawn in this figure represents the lognormal distribution based on the mean streak spacing $\bar{\lambda}^*$ and variation coefficient $\phi = \sigma / \bar{\lambda}$, where $\sigma$ is the standard deviation of $\bar{\lambda}^*$. Smith et al. and Iritani et al. have reported that in wall turbulence of Newtonian fluid such a histogram agrees with a lognormal distribution in the linear sublayer and in the buffer region. In this study, similar results were confirmed for water flow. On the other hand, in the flow of drag-reducing surfactant solution, there appears the second small peak at large $\lambda^*$ value in the vicinity of the wall, as the data in Fig. 12 show. (A second small peak is observed at about $\lambda^*=250$ in Fig. 12(a) and $\lambda^*=300$ in Fig. 12(b).) Such a histogram with plural peaks can be seen at some distance from the wall in Newtonian fluid. Therefore, in the drag-reducing flow, the low-speed streaks are considered to locate at some distance away from the wall on the average.

The mean streak spacing is plotted against $y^*$ in Fig. 13 for the 500 ppm surfactant solutions with a $DR$ of 60% and 26%, respectively, in comparison with that for water. The mean streak spacing for water agrees well with the results of Iritani et al., in which the spacing decreases with decreasing $y^*$. On the other hand, in the flow of a remarkable drag-reducing surfactant solution, it increases rapidly with decreasing $y^*$ in the small $y^*$ region. A similar phenomenon has been observed for dilute polymer solutions. Considering that the low-speed streak is formed by a longitudinal vortex near the wall, it is speculated that the nondimensional wall-normal distance $y^*$ of the center of streamwise vortices is larger for the flow of large $DR$ compared with that for Newtonian fluid flow, because the streak spacing becomes most dense at some distance from the wall in the drag-reducing flow.

Figure 14 shows the variation of $\bar{\lambda}^*$ for the 1 000 ppm surfactant solution. In this case, the minimum value of $\bar{\lambda}^*$ is much larger than that for the 500 ppm solution.

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**Fig. 11** Intermittency of low-speed streaks (water flow, $Re=4900$)

**Fig. 12** Histogram of spanwise streak spacing

(a) CuTASal 500 ppm $Re=10 000$, $DR=60\%$

(b) CuTASal 1 000 ppm $Re=20 000$, $DR=62\%$

induced state never occurs in polymer solution). However, it is evident that the mean streak spacing very near the wall increases as $DR$ increases in both fluids.

Putting together the experimental results mentioned above, it is concluded that the scale of the streamwise vortex near the wall increases as $DR$ increases.

5. Conclusion

To clarify the mechanism of drag reduction in the flow of surfactant solution, the mean velocity profiles, the distributions of streamwise turbulence intensity, and the characteristics of the low-speed streaks in turbulent channel flow are obtained. The results are summarized as follows.

1. In the flow of the surfactant solution with large drag reduction rate, the peak value of the streamwise turbulence intensity $u_{rms}/u_c$, which is made nondimensional by wall variables, is much larger than that for Newtonian fluid flow. Moreover, there is a plateau region around its peak in the profile of $u_{rms}/u_c$.

2. In the drag-reducing flow, low-speed streaks are observed most often at some distance from the wall, and the streaks decrease rapidly when approaching the wall.

3. In the drag-reducing flow of high density (1000 ppm) surfactant solution, the low-speed streaks appear intermittently at the Reynolds number smaller than those for the 'hump' of the friction factor versus Reynolds number ($\text{'hump'}-Re$) curve, and the flow seems not to be fully turbulent.

4. The mean streak spacing $\lambda^+$ very near the wall increases as the drag reduction rate $DR$ increases in the surfactant solution as well as in the polymer solution.

5. In the flow of drag-reducing viscoelastic fluid such as surfactant solution and polymer solution, the scale of the streamwise vortex near the wall


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increases, and the center of the vortex moves away from the wall as $DR$ increases.

References


