TURBULENCE MODULATION AND INSTABILITY INDUCED BY SURFACTANT ADDITIVES IN BACKWARD-FACING STEP FLOW

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ABSTRACT

The water flow is largely changed by adding surfactant because of the fluid viscoelasticity, which is known as the Toms effect. The trubulent state can be stabilized in the straight pipe flow of surfactant solution and therefore the wall frictional drag is significantly reduced. Whereas, the enhancement of turbulence by viscoelasticity also can be observed in surfactant flow, which increases the turbulent instability along the bended the flow line. Therefore we will try to find the conditons under which the conflict between suppression and enhancement of viscoelasticity on turbulence happens.

In this study, we performed a series of experimental investigations on the viscoelastic flow through a backward-facing step (BFS) to obtain the turbulence statistics profiles along the streamwise direction in a separated shear layer using a PIV system. As a result, in the separated shear layer flow with surfactant additive, we found two flow conditions depending on the balance between surfactant concentration of viscoelastic fluid and shear rate. Firstly, the suppressed-turbulence condition was observed. Secondly, the enhanced-turbulence condition was clarified, accompanied with meandering main flow to the wall-normal direction in the instantaneous velocity field and the meandering main stream in enhanced-turbulence condition was studied in detail at some points along the streamwise direction. Finally, we evaluated the limits between suppression and enhancement of viscoelasticity on turbulence and made the meandering conditions map for the surfactant viscoelastic flow. Based on the map we found that the increase in viscoelastic force with surfactant concentration results to the expansion of the stable region.

1. INTRODUCTION

By adding surfactant or water-soluble long-chain polymer, the fully developed turbulent water flow shows dramatic viscoelasticity, wherein the vortices are suppressed resulting to the remarkable decrease in turbulent fricion drag (Toms, 1948). This unique turbulent transfer phenomenon is the so-called "Toms effect" which has attracted interest of many researchers due to its importance in industrial application. It has been proved experimentally that the decrease in wall shear stress (skin friction) is up to 60% in surfactant turbulent channel flow by Li et al. (2004).

When viscoelastic laminar flow goes through the serpentine channel, however, the turbulence is enhanced compared with the Newtonian flow reported by Tatsumi et al. (2011). It should be attributed to the influence of the normal stress, which is one of the characteristics of viscoelastic fluid flow.

But so far the separated turbulent viscoelastic flow is poorly studied, and thus we are aimed to perform experimental investigations on the turbulent Backward-Facing Step (BFS) flow of surfactant solution by using a Particle Image Velocimetry (PIV) device. The BFS flow contains significant variations of the mean velocity and turbulence statistics along the streamwise direction. Although the wall-normal turbulent fluctuations at upstream are suppressd by the wall, it is expected that the turbulence is enhanced with the disappearing of the wall on one side at inlet of the BFS flow. Meanwhile, the viscoelasticity plays a suppressing role on vortices in the separated shear layer. In addition, it is proved that the behavior of the separated shear layer is determined by several parameters, such as Reynolds number Re (inertial force / viscous force), normal-stress / viscous force and relaxation time of flow (distance from a separated point / velocity) / that of the viscoelastic fluid (because there exists the relaxation process of the shear deformation near the wall).

The main objective of this study is to clarify the basic characteristics of the complicated BFS flow to make contribution to the numerical analysis research. Therefore, we performed a series of experimental investigations with changing the concentration of surfactant solution and Re, which are related to the relaxation time. Besides, we also

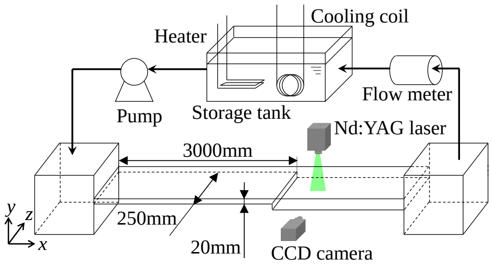

Figure 1. Schematic diagram of the closed circuit water loop.

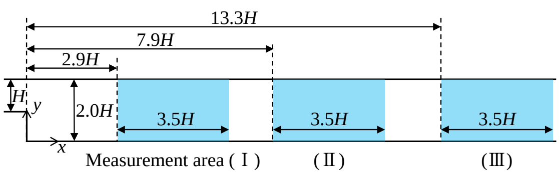

Figure 2. Measurement area for PIV.

measured the turbulence statistics at different positions, corresponding to different relaxation times of flow.

2. EXPERIMENT APPARATUS AND PROCEDURE

As shown in Figure 1, the experiments were carried out with a closed-circuit water loop, which consists of a two-dimensional channel and a sudden expansion geometry with expansion ratio of 1:2. The flow temperature was controlled at 298.2 ± 0.2 K. Figure 2 shows the measurement areas of PIV device. PIV measurement was carried out at three positions downstream from the expansion point (x = 0) to take a series of investigation on the mean velocity and turbulence statistics profiles. The picture field was set to cover an area of 3.5H × 2.0H at any point. This PIV system was utilized to measure the instantaneous velocity field u-v in the x-y plane by tracing nylon particles with a mean diameter of 4.1 μm. Turbulent statistics were obtained by averaging 500 velocity fields.

As a viscoelastic fluid known for giving rise to the Toms effect, the surfactant solution was prepared by adding same mass of cationic surfactant CTAC (cetyltrimethyl ammonium chloride) and sodium salicylate (NaSal) to the tap water. The concentrations of CTAC solutions were 0, 25, 40, 80, 150 and 300 ppm. The Reynolds number Re (Eq. 1) ranges from 1.0×10^4 to 3.0×10^4, and is based on the channel height H and the mean bulk velocity U_b which is calculated from the flow rate tested by an electromagnetic flow meter.

$$\mathrm{Re} = \frac{U_b H}{\nu} \qquad (1)$$

At these Reynolds numbers, the flow of water (CTAC concentration is 0 ppm, i.e. the Newtonian fluid) was fully turbulent in the smooth channel. In the present paper, we use the kinematic viscosity of water υ as that of the surfactant solution considering the low concentration of CTAC.

3. RESULTS AND DISCUSSION

3.1. Definition of Character

Hereafter, $\langle\ \rangle^*$ denotes the normalization by the characteristic parameters which are used to define the Reynolds number, $\langle\ \overline{\ }\ \rangle$ the ensemble average of the turbulent statistics based on 500 velocity fields, and $\langle\ \rangle'$ the velocity fluctuation.

3.2. Turbulence Statistics

Firstly, we focus on the turbulent statistics to clarify that the turbulence in the BFS flow of the surfactant solution is suppressed or enhanced by viscoelasticity. Figure 3 shows respectively the profiles of the streamwise mean velocity (a), turbulence statistics of turbulent intensities u (b) and v (c) at Re = 1.5×10^4, Reynolds shear stress (d) and turbulence production term (e).

Figure 3(a) displays that the recirculation region marked by dashed line is formed at upstream. The distribution of streamwise mean velocity downstream is similar with that in the turbulent channel flow. Within the region of $x^* \leq 5.5$, the profiles of the streamwise mean velocity for solutions at 40 and 150 ppm are almost same, while they become very different in the region of $x^* > 5.5$. The difference should be attributed to that the flow influencing factor of characteristic time scale, presented as relaxation time, changes with concentration.

For solution at 150 ppm, the magnitude of u_{rms} is almost unchanged, inversely the wall-normal turbulent intensity v_{rms} decreases downstream. And this phenomenon can be explained combining the results that the variation and redistribution of each fluctuation components in viscoelastic flow compared with the Newtonian one from DNS reported by Voropaev and Dimitrieva (2013).

Furthermore, it can be found in Figures 3(d) and (e) that the Reynolds shear stress and turbulence production decrease obviously downstream for solution at 150 ppm, which is due to the decreases of v_{rms} and the correlation coefficient of fluctuating components (u' and v'). For solution at 40 ppm, all turbulence statistics increase dramatically compared with those in water flow around the position of x^* = 8.1. Especially, the Reynolds shear stress and turbulence production are very large due to the enhancement of the turbulence in surfactant solution flow, which means the local wall friction is increased in surfactant flow. Under the dynamically balanced state, the enhancement of turbulence in the fully developed viscoelastic flow at high Re is rarely reported, therefore it should be a unique phenomenon under unbalanced state in the BFS flow. Whereas, the turbulence statistics decrease

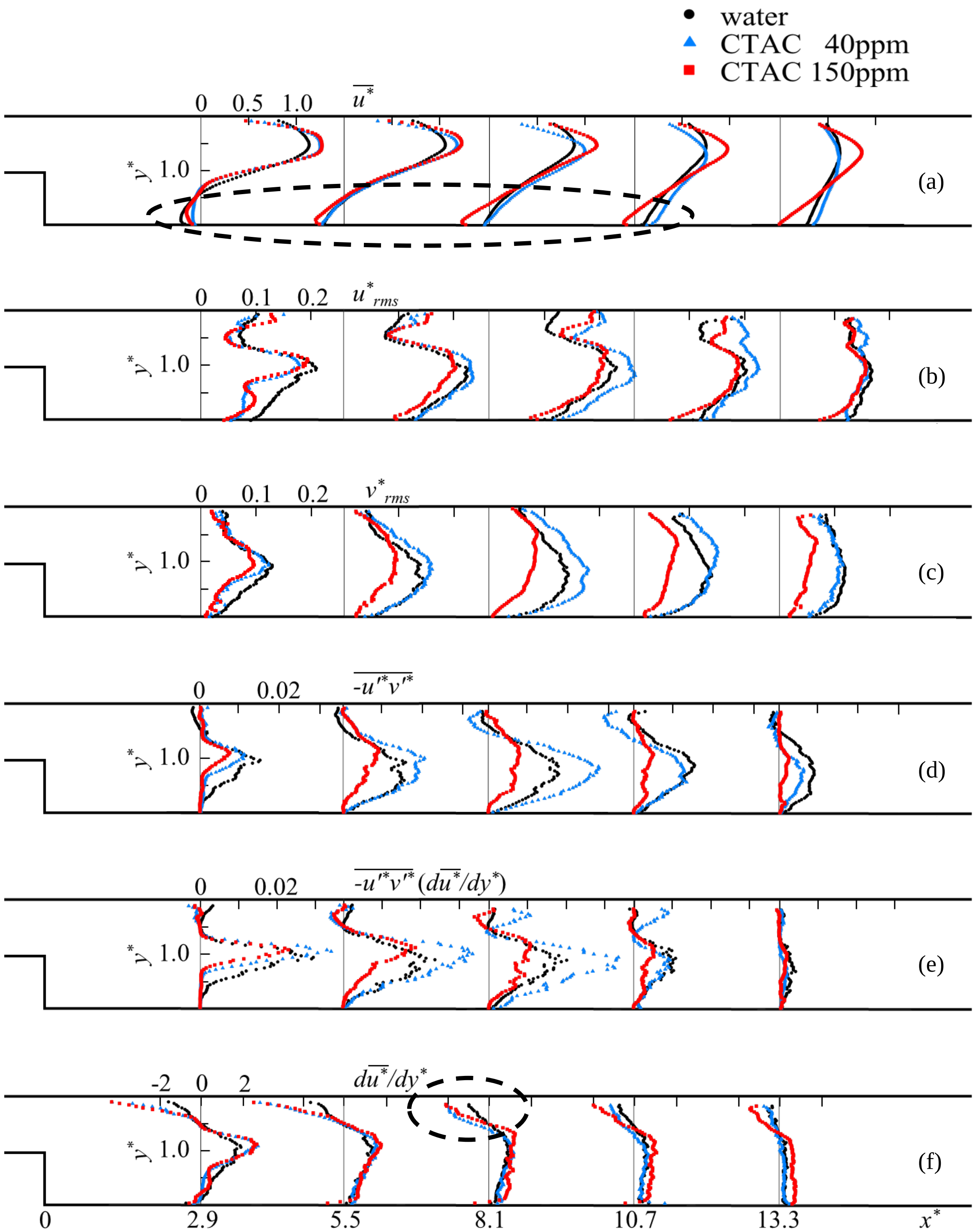

Figure 3. Turbulence statistics profiles at Re = 1.5×10^4. (a) Mean streamwise velocity, (b) Root mean square of streamwise velocity fluctuations, (c) Root mean square of wall-normal velocity fluctuations, (d) Reynolds shear stress, (e) Turbulence production and (f) Mean streamwise velocity gradient.

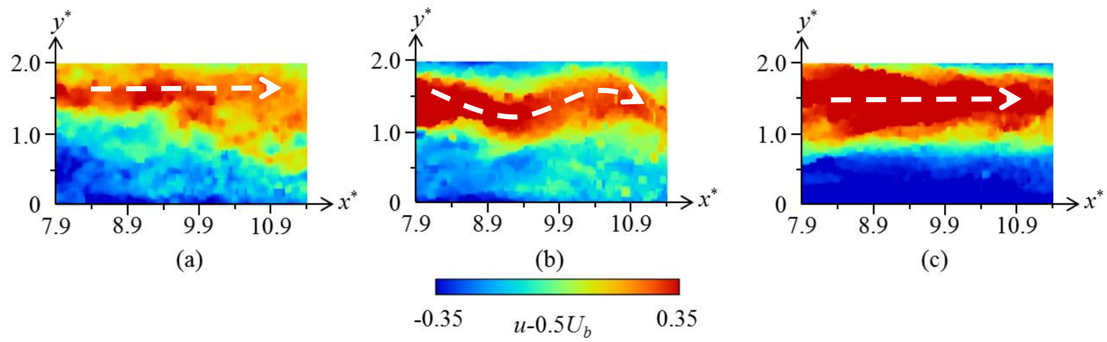

Figure 4. Instantaneous velocity field at Re = 1.5×10^4 in the measurement area Ⅱ. (a) water, (b) surfactant solution 40ppm and (c) 150ppm.

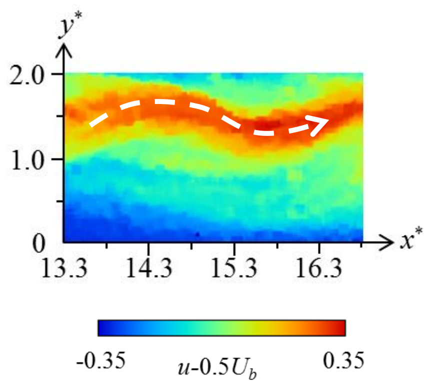

Figure 5. Instantaneous velocity field of surfactant solution 150ppm at Re = 1.5×10^4 in the measurement area Ⅲ.

noticeably near the position of $x^* = 13.3$, which resulting from that the streamwise mean velocity gradient decreases with the relaxation of the streamwise mean velocity leading to the decreases of Reynolds shear stress and turbulence production. Ultimately, the local enhancement of turbulence by viscoelasticity makes the flow more unstable and the instability affects the flow condition of solution at 40 ppm under Re = 1.5×10^4.

3.3. Instantaneous Velocity Field

The flow instability caused by viscoelasticity under certain conditions is presented above in secton 3.2, and it will be studied in the following part that whether the instability can be caused by the meandering in flow in *y* direction. Figure 4 shows the streamwise instantaneous velocity fields in area of $x^* = 7.9$–11.4 (the measurement area of II shown in Figure 2). The Reynolds number is set at 1.5×10^4 for each testing procedure: water flow (a) and CTAC flows at 40 ppm (b) and 150 ppm (c). It can be clearly seen from Figure 4(b) that the CTAC flow at 40 ppm meanders in *y* direction. The meander of the main stream might result in the local increase of velocity fluctuations around $x^* = 8.1$. The wavy motion of the main stream may be caused by the viscoelastic effect of the fluid. The stabilizing action of viscoelastic fluid supresses the irregular motions of the relatively small scale vortices. At the same time, flow fluctuations caused by larger scale vortices result in unstable actions which give rise to viscoelasticity even in a smooth channel (Motozawa et al., 2014). In the BFS flow, the boundary condition rapidly changes after the wall on one side disappears and the flow is released from the confinement of the wall. These factors above trigger the development of wavy flow motion after the BFS. The generation of the normal-stress difference is studied as a factor of flow instability which is peculiar to viscoelastic fluid. In the viscoelastic fluid flow, the normal-stress difference is generated by the combined effects of the streamwise velocity gradient and surfactant concetration. As the main stream flows away from the upper wall to the bottom one, the normal stress in *y* direction becomes larger with its increasing velocity gradient. Then, the oncoming main stream is pushed back by normal-stress and pressure gradient. After these actions, the main stream meanders and generates apparent turbulent fluctuations. The increased velocity gradient (marked by dashed line) can be observed in Figure 3(f). That is the reason why the flow instability is induced by the combined effects of the normal-stress difference decided by the concentration of the surfactant solution and Re representing pressure gradient.

We have studied two flow conditions including the flow downstream in section 3.2. Let us now consider the relaxation process of the flow instability. At certain concentration, there exists a relaxation process to release the shear deformation near the wall depending on the relaxation time ratio of the flow to the viscoelastic fluid, and thus the flow instability disappears gradually along the streamwise direction. On the contrary, based on Figure 3(f), we can conclude that the increase of the wall-normal difference is induced by the increase of the velocity gradient, and so the flow instability grows up along the streamwise direction. Consequently, the flow can reach an equilibrium state at one certain position based on the

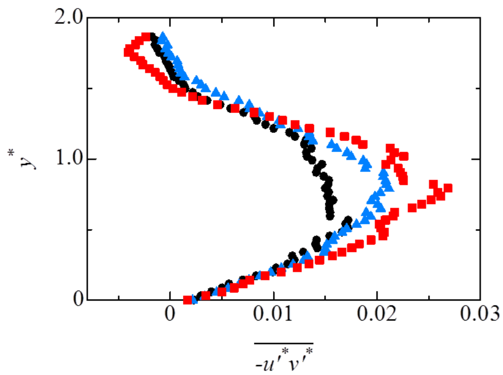

Figure 6. Reynolds shear stress profiles at Re = 2.5×10^4, x/H = 8.1.

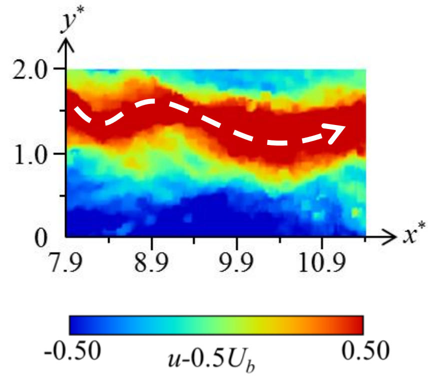

Figure 7. Instantaneous velocity field of surfactant solution 150ppm at Re = 2.5×10^4 in the measurement area Ⅱ.

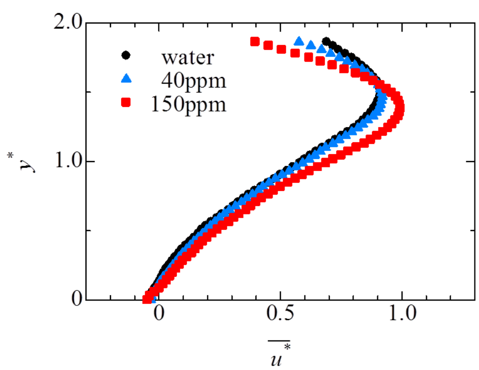

Figure 8. Mean streamwise velocity profiles at Re = 2.5×10^4, x/H = 8.1.

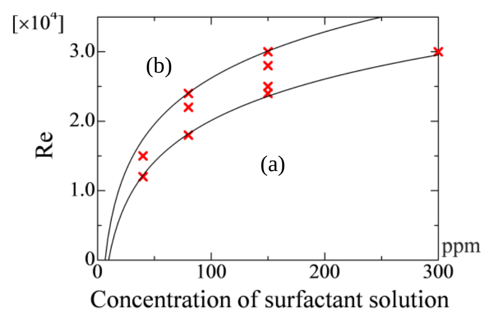

Figure 9. Profile of meandering conditions.
(a) stability area and (b) instability area.

above conflict status along the streamwise, and therefore the meandering of the main stream can be observed.

Figure 5 shows the streamwise instantaneous velocity fields at concentration of 150 ppm, Re = 1.5×10^4 in area of x^* = 13.3–16.8 (the measurement area of Ⅲ). It displays that the main stream meanders and as discussed previously, the Reynolds shear stress and the turbulence production decrease dramatically due to the decrease in its velocity gradient. Both Figures 4(b) and 5 display that the width of the main stream is about $H/2$ (half of the channel height at upstream of the BFS flow), which means that the size of the largest scale vortices induced by main stream is about $H/2$ too, namely one-fourth of the channel height of the BFS. In general, the size of the largest scale vortices in turbulent channel flow is equal to the half channel height. Consequently, the main stream contains the flow feature at upstream of the BFS flow, which proves again that the flow does not develop from the sudden change of the boundary condition caused by the disappearance of the wall on one side of the BFS flow.

3.4. Meandering Conditions

The flow instability (following the enhancement of the turbulent statistics) caused by the meandering of main stream is also observed in the CTAC flow of 150 ppm at Re = 2.5×10^4, as shown in Figures 6 and 7. By contrast, the Reynolds shear stress distribution and the profile of streamwise mean velocity in the CTAC flow of 40 ppm is very similar to those of the water flow. The reason is that the surfactant flow becomes very similar with water flow due to the breakage of micellar structure under very high Re.

Given the above, it can be concluded that the flow instability is caused by the combined effects of Re, normal-stress / viscous force and relaxation time of flow / that of the viscoelastic fluid. Therefore, we tried to find the relationships between Re and concentration of surfactant viscoelastic fluid, the combined effects of which give rise to the meandering main stream and fluctuations. Figure 9 shows the relations of meandering conditions with Reynolds number and CTAC concentration, and it is shown as the area between the curves. In the area (a) in Figure 9, the stability of the flow increases while the Reynolds shear stress decreases dramatically, conversely in the area (b), the surfactant flow becomes almost same with water flow due to the breakage of micellar structure. Besides, the stability area expands with concentration of CTAC. The meandering area also expands with concentration of CTAC. The flow becomes the most unstable in the meandering conditions. As it approaches the area (b), the flow becomes similar with water flow.

CONCLUSION

In this study, we performed a series of experimental investigations on the viscoelastic flow through a backward-facing step (BFS) to obtain the turbulence statistics profiles along the streamwise direction in a separated shear layer using a PIV system. As a result, in the separated shear layer flow with surfactant additive, we found two flow conditions depending on the balance between surfactant concentration of viscoelastic fluid and shear rate. Firstly, the suppressed-turbulence condition was observed, wherein the wall-normal turbulent intensity decreases. Secondly, the enhanced-turbulence condition was clarified, accompanied with meandering main flow to the wall-normal direction in the instantaneous velocity field and the meandering main stream in enhanced-turbulence condition was studied in detail at some points along the streamwise direction. Finally, we evaluated the limits between suppression and enhancement of viscoelasticity on turbulence and made the meandering conditions map for the surfactant viscoelastic flow. Based on the map we found that the increase in viscoelastic force with surfactant concentration results to the expansion of the stable region.

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