TURBULENCE STATISTICS OF TURBULENT BOUNDARY LAYER FLOW FOLLOWING INJECTION OF DRAG-REDUCING SURFACTANT SOLUTION

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Abstract To investigate streamwise variations of turbulence statistics in the wide range of the drag reduction ratio for the zero-pressure-gradient turbulent boundary layer flow due to the injection of drag-reducing nonionic surfactant solutions, we performed the laser-Doppler velocimetry (LDV) measurement at a new experimental apparatus with the larger size than previous one. The drag reduction ratio up to 76% could be obtained, at which the mean velocity in wall-units was beyond the Virk's ultimate for polymer solutions.

INTRODUCTION

As reviewed by White & Mungal [1], the dependence of turbulence statistics on the drag reduction ratio was more complex compared to the turbulent channel flow owing to the history effect of the polymer (or network structures of surfactant micelles)-turbulence interaction. Quite recently, Graham [2] reported that the most striking feature of rheological drag reduction phenomenon was the existence of a so-called maximum drag reduction (MDR) asymptote. So far, we have clarified the difference in the development of turbulence statistics and structures for the drag-reducing turbulent boundary layer between heterogeneous and homogeneous nonionic surfactant solutions (see [3, 4] for details). In these studies, however, the maximum drag reduction ratio was 50%, so that the MDR phenomenon could not be investigated, which was mainly due to the size limitation of the experimental setup used. In this study, therefore, we first constructed a new experimental apparatus with the larger size of the test section, and then performed two-component LDV measurements for the zero-pressure-gradient turbulent boundary layer flow including the MDR region.

EXPERIMENTAL OUTLINE

Figure 1 shows the present experimental apparatus, which is the closed-loop water tunnel. The cross section is 400 mm $\times$ 400 mm, and the length is 3000 mm which is twice larger than our previous one (cf. [4]). Figure 2 shows the test plate with injection slot, which is installed in the water tunnel. The slit with streamwise and spanwise length of 1.0 mm and 200 mm was flush-mounted into the test plate. The slit, which consisted of two parallel plates with the gap of 0.5 mm, was located at $x = 400$ mm from the leading edge and inclined at 30° to the flat plate (see [4]). A 0.8-mm diameter trip wire fixed at $x = 146$ mm was used to develop the boundary layer on the test plate. The Working fluid was circulated by a stainless steel centrifugal pump with the inverter control. The free-stream velocity U_e was set at about 300 mm/s.

The present two-component LDV system with 300 mW argon-ion laser was used in the back scatter mode. LDV measurements were made at six different locations downstream from the leading edge $x = 800$ to 2500 mm (see Fig. 2). The nonionic surfactant used here was AROMOX, which mainly consisted of oleyldimethylamineoxide (ODMAO), developed by Lion Akzo Co., Ltd., which was dissolved in tap water. The concentration of ODMAO was 500 ppm by weight. The flow rate of the injection was set at 1.45×10^{-2} L/s. The temperature of working fluids was $20.0 \pm 0.3^\circ$C using the large-size water cooler. For further details of the present LDV system and nonionic surfactant soluions, readers are referred to our previous studies (see Tamano et al. [3, 4]).

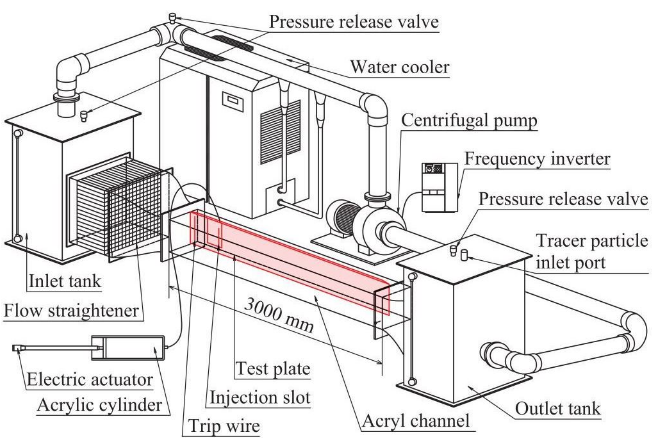

Figure 1. Experimental setup.

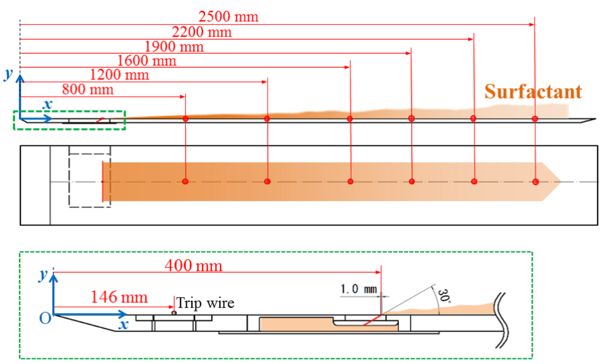

Figure 2. Test plate with injection slot.

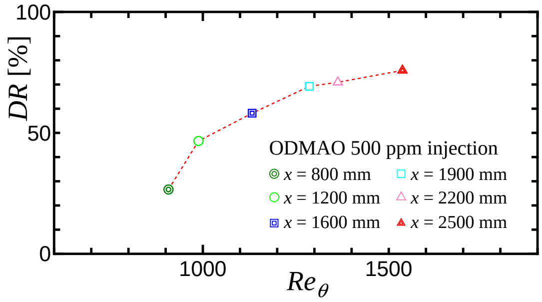

Figure 3. Drag reduction ratio versus Reynolds number.

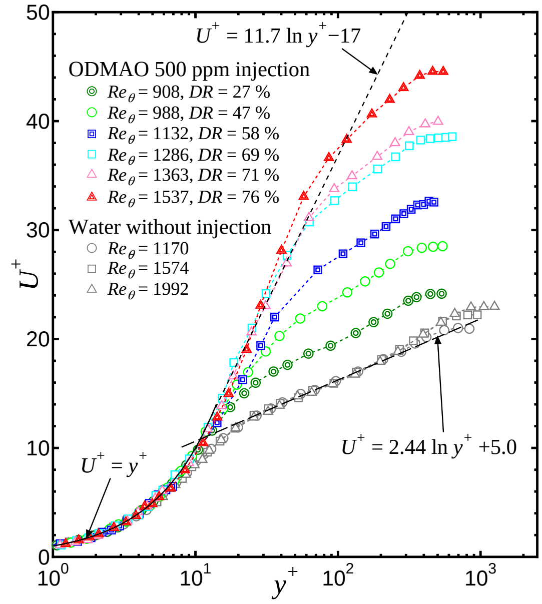

Figure 4. Mean velocity profile.

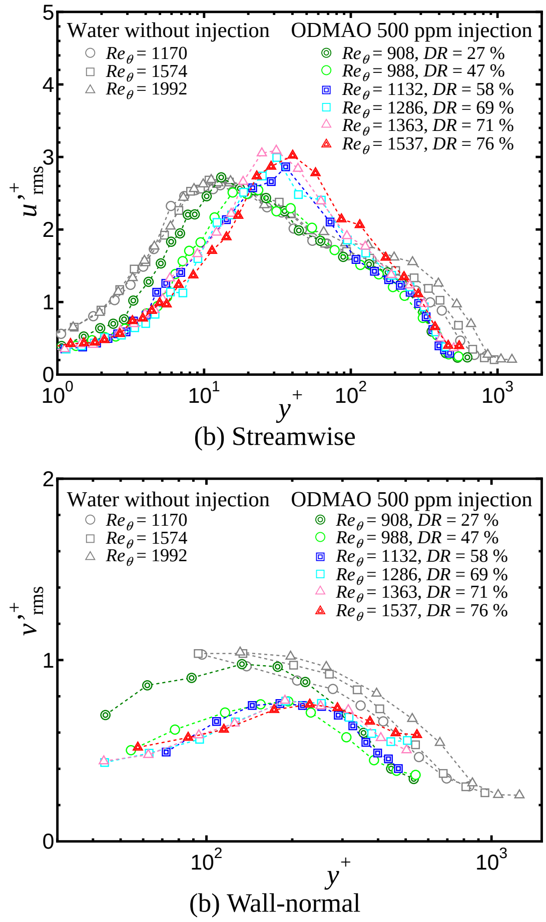

Figure 5. Profiles of turbulence intensities.

RESULTS AND DISCUSSIONS

Figure 3 shows the drag reduction ratio DR versus the momentum-thickness Reynolds number Re_θ (see [4] for the definition of DR). The DR increases with increasing Re. The maximum drag reduction ratio of 76% at $x = 2500$ mm, which corresponds to the MDR region, is much larger than our previous study ($DR = 50\%$ at $x = 1000$ mm) (cf. [4]).

Figure 4 shows the profile of mean velocity scaled by the friction velocity $U^+ = U/u_\tau$. The abscissa y^+ is the distance from the wall scaled by the viscous length scale. The dotted line represents the Virk's ultimate profile [5], ($U^+ = 11.7$ ln $y^+ - 17$) for polymer solutions. It is found that, with going downstream or with the increase in the amount of drag reduction, the mean velocity U^+ increases and the slope at $y^+ > 10$ becomes larger. At the most downstream location ($x = 2500$ mm), the value of U^+ for surfactant injection is beyond the Virk's ultimate profile for polymer solutions, as pointed out by Zakin et al. [7] for surfactant solutions.

Figures 5(a) and 5(b) show distributions of streamwise and wall-normal turbulence intensities scaled by the friction velocity, $u'^+_{\rm rms} = u'_{\rm rms}/u_\tau$ and $v'^+_{\rm rms} = v'_{\rm rms}/u_\tau$, respectively. At the large drag reduction case ($DR \geq 58\%$), the maximum of $u'^+_{\rm rms}$ is larger than that of water, and its wall-normal location is further away from the wall, as also seen in our DNS [6]. The $v'^+_{\rm rms}$ except at the most upstream location is much smaller than that for the water, which is consistent with previous findings [1, 2, 3, 4, 6].

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