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Experimental investigation on streamwise development of turbulent structure of drag-reducing channel flow with dosed polymer solution from channel wall

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ABSTRACT

Streamwise development of the turbulent structure of the drag-reducing channel flow by dosed polymer solution from a channel wall was investigated experimentally. Particle image velocimetry (PIV) was employed to investigate the turbulent structure in the x–y plane and we carried out PIV measurements downstream at three positions: 250 mm (position 1), 800 mm (position 2), and 1350 mm (position 3) from the leading edge of the dosing wall. The Reynolds number based on the channel height and the bulk mean velocity was set to 40,000. 100 ppm of weight concentration of dosing polymer solution was dosed at 10.5 L/min from the whole surface of the dosing wall. As a result of the experiments, Reynolds shear stress and root mean square (RMS) of the wall-normal velocity fluctuation gradually decreased downstream. Corresponding to this decrement, the drag reduction rate developed downstream and drag reduction rate of about 63% was obtained at position 3. In addition, the results of the analyses by Galilean decomposition and swirling strength showed that the suppression of the ejection around the vortical core became stronger downstream. These changes of the turbulent structure in the streamwise direction led to the development of drag reduction downstream. However, near the starting point of the polymer dosing (position 1), drag reduction was not obtained but drag increases. In addition, the unique turbulent structure was observed at this position.

1. Introduction

Some kinds of high-molecular-weight polymer solutions significantly reduce the skin frictional drag in turbulent flow even at rather dilute concentrations of tens of parts per million (ppm). This phenomenon was first reported by Toms (1948) and thus came to be known as the Toms effect. This drag-reducing effect has the major benefit of reducing energy consumption in industrial applications such as district heating/cooling systems (Takeuchi et al., 2009). In the case of such an internal flow, many researchers have investigated the drag-reducing effects of homogeneous polymer solutions experimentally (Warholic et al., 1999, 2001; Ptasinski et al., 2001; White et al., 2004) or using numerical simulations (Den Tooder et al., 1997; Kim et al., 2007). In particular, the fundamental work for the drag-reducing effect in pipe flow was carried out by Virk (1971, 1975). Virk pointed out that the drag reduction depends on the polymer characteristics and polymer concentration, but saturates beyond a certain value. This limitation of the drag reduction is called the maximum drag reduction (MDR) and Virk's asymptote was defined.

Recently, there has been a growing need for novel techniques to achieve drag reduction for an external flow, such as the flow around ship hulls. Regarding shipping industry, the hulls of cruising ship experience a large skin frictional drag and this skin frictional drag occupies approximately 80% of the total resistance of the cruising ship. If this skin frictional drag can be reduced, it will produce great savings in fuel, cost of marine transportation,

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and travel time. For reducing the skin frictional drag in external flow, several drag reduction techniques for ship hulls such as riblets (Walsh, 1983), and microbubble (Kitagawa et al., 2005; Murai et al., 2007) were suggested, but these techniques have not yet reached practical level. Toward such a goal, we aim for the application of Toms effect to external flow, and suggested a novel method for reducing the skin frictional drag by dosing polymer solution from the whole surface of the channel wall. We called this method “wall dosing” (Motozawa et al., 2009). Moreover, we are developing a new paint for ship hulls that exhibits the Toms effect by continuously releasing a small amount of polymer (Senda et al., 2010; Motozawa et al., 2010). This paint has a function of leaching out the polymer and eventually reduces the skin frictional drag owing to the effect of dissolved polymer when the ship is cruising.

In contrast, one of the most well-known methods for achieving drag reduction for an external flow is to inject polymer solution from a slot; we call this method “slot injection” in this paper. There have also been a large number of studies as the inhomogeneous drag reduction by slot injection. Tiederman et al. (1985) found that large drag reduction occurred by injecting polymer directly into buffer layer but this drag reduction rate decreases gradually downstream. Moreover, they investigated the relationship between the drag reduction and wall-layer structure of the drag-reducing flow, and reported that the dimensionless spanwise spacing of wall-layer structure streaks increases and the bursting rate decreases in the drag-reducing flow. In addition to this knowledge, Walker and Tiederman (1989) measured the profiles of the instantaneous polymer concentration in the same drag-reducing channel flow by laser induced fluorescence (LIF). They examined the mixing process of the injected polymer solution downstream of the slot, and discussed the action of polymer solution in the turbulent flow by clarifying how the turbulent mixing is modified and damped. On the other hand, regarding the relationship between the amounts of injected polymer, Vdovin and Smol’yakov (1981) measured the local polymer concentration in the turbulent boundary layer by tracking the polymer samples from the flow at various points downstream of the slot, and developed scaling laws for the diffusion of wall-injected polymer and phenomenological flow region. In addition, Winkel et al. (2006) measured the drag reduction rate and the near-wall polymer concentration in the near-wall region at a high Reynolds number. They investigated the relationship between the local drag reduction and the polymer diffusion by using the scaling law developed by Vdovin et al. This investigation was of great significance for the study of heterogeneous drag reduction.

However, the drag reduction rate is not only affected by the amount of injected polymer, but also is closely related to the situation of turbulent flow. Many DNS studies (Tsukahara et al., 2010; Yu and Kawaguchi, 2003; Min et al., 2003) have been carried out, and they reported that the Weissenberg number, which is the ratio of relaxation time of polymer to characteristic time of turbulent flow, has a significant effect on the drag reduction rate, and high drag reduction can be achieved by suppressing the production of turbulence for high Weissenberg number. In addition, these studies can lead to understand the spatial vortex structure which cannot be observed from experimental study. Moreover, Iwamoto et al. (2005) simulated turbulent channel flow with damping of only the near-wall turbulence and reported that large drag reduction was obtained by controlling only the near-wall turbulence. According to above knowledge, drag reduction can be achieved by controlling only the near-wall turbulence. Therefore, in the case of the wall dosing method, because polymer can be provided downstream continuously and dosed polymer solution would accumulate in the near-wall region, it is possible that the frictional drag can be reduced effectively comparable to slot injection. Moreover, it is very important to investigate the turbulent structure of the drag-reducing flow by dosed polymer solution to clarify the mechanism of the drag reduction phenomenon.

In our previous study (Motozawa et al., 2009), we reported that evidently the drag reduction can be achieved by the wall dosing method and the drag reduction rate has a relationship with the amount of dosed polymer. Moreover, we measured the instantaneous velocity field u–v in the x–y plane by using PIV (Motozawa et al., 2012a), and reported that streamwise turbulent intensity increases, but wall-normal turbulent intensity and Reynolds shear stress decrease in the only near-wall region. In order to discuss the near-wall turbulent structure of the drag-reducing flow by the dosed polymer solution in more detail and to obtain new information about the drag reduction mechanism, we analyzed the PIV results with four quadrant analysis, Galilean decomposition and swirling strength, and reported the characteristic coherent structure of the drag-reducing flow by the dosed polymer solution from the wall (Ishitsuka et al., 2011a,b).

However, because polymer concentration boundary layer develops from the starting point of dosing polymer solution in the wall dosing method, this characteristic turbulent structure of the drag-reducing flow should change gradually downstream from the leading edge of the dosing wall. Some researchers investigated the streamwise variation of the turbulent structure of the drag-reducing flow. Tamano et al. (2011) performed direct numerical simulation of a boundary layer flow of a polymetric fluid with FENE-P model and investigated the streamwise variation in turbulent statistics and structures in turbulent boundary layer. On the other hand, in the slot injection, Hou et al. (2008) investigated the streamwise development of the turbulent statistics in the turbulent boundary layer drag-reducing flow by injected polymer solution from the slot. However, we think that the streamwise development of the turbulent statistics by the wall dosing method is different from that by the slot injection, due to the difference of drag reduction development between slot injection and wall dosing method. Moreover, how coherent structure would change by the polymer exists in the near-wall region and how the change in the coherent structure influences on the drag reduction are still unclear. Therefore, we focused on the streamwise variation in the coherent structure of the drag-reducing channel flow by dosed polymer solution from the whole surface of the channel wall in this study.

2. Experiment

2.1. Experimental apparatus

Fig. 1 shows a schematic diagram of the experimental apparatus including (a) the flow system and (b) the cross section of the channel with a dosing wall. The flow system consists of a closed-circuit water loop having a two dimensional channel with a dosing wall. The channel was made of transparent acrylic, with a length of 6000 mm, a width of 500 mm, and a height of 40 mm ($2h$). A honeycomb rectifier with a grating space of 10 mm was set at the channel entrance to remove large eddies. A storage tank was equipped with a heater and an agitator to adjust the fluid temperature. The temperature of the flowing fluid was kept stable at 25 ± 0.1 °C during the experiments.

The wall for dosing of polymer solution was made of an SUS filter with a size of 450 mm × 450 mm. The pore size of this filter was 150 μm. Three dosing walls were attached to one side of the channel in a line. The leading edge of the dosing wall was located 2300 mm downstream from the entrance of the channel. Polymer solution can be dosed into the channel flow from the whole surface

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