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Characteristic turbulent structure of a modified drag-reduced surfactant solution flow via dosing water from channel wall

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ABSTRACT

The modification of the near-wall structure is very important for the control of wall turbulence. To ascertain the effect of near-wall modulation on the viscoelastic drag-reduced flow, the modified characteristics of a surfactant solution channel flow were investigated experimentally. The modulation was conducted on the boundary of the channel flow by injecting water from the whole surface of one side of the channel wall. The diffusion process of the injected water was observed by using the planar laser-induced fluorescence technique. The velocity statistics and characteristic structure including the spatial distributions of instantaneous streamwise velocity, swirling strength, and Reynolds shear stress were analyzed based on the velocity vectors acquired in the streamwise wall-normal plane by using the particle imaging velocimetry technique. The results indicated that the disturbance of the injected water was constricted within a finite range very near the dosing wall, and the Reynolds shear stress was increased in this region. However, the eventual drag reduction rate was found to be increased due to a relatively large decrement of viscoelastic shear stress in this near-wall region. Moreover, the flow structure under this modulation presented obvious regional characteristics. In the unstable disturbed region, the mixing of high-speed and low-speed fluids and the motions of ejection and sweep occurred actively. Many clockwise vortex cores were also found to be generated. This characteristic structure was similar to that in the ordinary turbulence of Newtonian fluid. Nevertheless, outside this disturbed region, the structure still maintained the characteristics of the drag-reduced flow with non-Newtonian viscoelastic additives. These results proved that the injected Newtonian fluid associated with the modified stress distribution creates a diverse characteristic structure and subsequent enhanced drag reduction. This investigation can provide the experimental basis for further study of turbulence control.

1. Introduction

The addition of certain kinds of surfactant additives or water-soluble polymers to turbulent flow can reduce the skin frictional drag. This phenomenon was discovered by Toms and is called the Toms effect (Toms, 1948). This drag-reducing effect has great potential for energy saving if it can be applied to industrial fields such as district heating/cooling systems (Takeuchi et al., 2009). Therefore, a large number of studies have been performed to explore the mechanism of this drag-reducing effect by water-soluble polymer solutions (Lumley, 1973; De Gennes, 1986; Den Tooder et al., 1997; Warholic et al., 1999; Min et al., 2003; Jovanovic et al., 2006; Benzi, 2010; Dubief et al., 2013) or surfactant additives (Zakin et al., 1996; Yu et al., 2004; Li et al., 2005; Tamano et al., 2009; Tsukahara et al., 2010). However, it still remains unclear how the coherent structures in the near-wall region act on the drag-reducing effect. If this point could be clarified, we would be able to realize active controls for turbulence so that a large drag reduction could be achieved with a tiny amount of additives, or heat transfer could be improved in the drag-reduced flow.

To attain drag reduction more effectively, there have also been many studies on reducing skin frictional drag of a turbulent flow by modifying only the near-wall coherent structures by adding viscoelastic additives. Regarding the usage of a polymer solution, one of the most popular methods for achieving drag reduction is to inject a polymer solution into wall turbulence from a slot. In this case, the injected polymer solution acts on the near-wall coherent

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structures and drag reduction occurs. Many researchers (Tiederman et al., 1985; Walker and Tiederman, 1989; Winkel et al., 2006; Hou et al., 2008) have investigated the near-wall turbulent structure and momentum transportation of the drag-reduced flow with injection of a polymer solution from a slot in the wall. In contrast, we proposed another method for achieving drag reduction by use of a polymer solution in our previous study (Motozawa et al., 2009). We call this method the "wall-dosing method". In this, the polymer solution injected from the whole surface of one side of the channel wall covers the near-wall region. By this wall-dosing method, we carried out experiments in a channel which had a dosing wall on one side, and revealed that significant drag reduction occurred and the Reynolds shear stress evidently decreased near the dosing wall (Motozawa et al., 2012a).

On the other hand, the effect of improvement of near-wall coherent structures on drag reduction was also considered by numerical simulation. Iwamoto et al. (2005) simulated a turbulent channel flow by damping only the near-wall turbulence, and reported that this could result in suppression of the turbulence in the entire region, and a large drag reduction was achieved. Fukagata et al. (2002) developed an identity for the skin friction coefficient in the turbulent channel flow. They reconfirmed that the near-wall Reynolds stress is very important for the prediction and control of wall turbulence. Therefore, it seems that the turbulent structure and stress distribution existing in the near-wall region play key roles in the prediction and control of wall turbulence, including drag-reduced turbulent channel flow.

Furthermore, considering the drag reduction caused by homogeneous surfactant additives in the turbulent flow, it is also of great interest how the viscoelasticity of the surfactant solution in the near-wall region affects the wall turbulence. It is well known that in a drag-reduced surfactant solution flow, the drag-reducing effect is usually weakened when the micelle network of the surfactant in the near-wall region is broken, and the corresponding viscoelasticity decreases in some cases, such as during flow under a high shear rate at a high Reynolds number (Hu and Matthys, 1995; Kawaguchi et al., 2002; Zhang et al., 2005) or under a high temperature (Lu et al., 1998; Kawada et al., 2013). Therefore, to ascertain the effect of the modified viscoelasticity, it is also important to investigate the flow structure of the drag-reduced flow when the surfactant solution does not work sufficiently in the near-wall region. In this study, the flow situation in which Newtonian fluid exists only near the wall in the viscoelastic drag-reduced flow can be assumed to be a similar flow model to such a modified drag-reduced flow. Thus, we realized this flow situation by dosing water into the viscoelastic drag-reduced channel flow from the whole surface of one side of the channel wall.

Moreover, this flow situation is the opposite condition to the aforementioned drag-reduced flow that is caused by covering the near-wall region with injected polymer solution, which was investigated in our previous study (Motozawa et al., 2009). To better understand both flow situations, the conceptual models for these two situations are presented in Fig. 1. Fig. 1a indicates the flow situation of the drag-reduced flow with dosing of the polymer solution from the channel wall. This flow situation was called NN2N (Non-Newtonian fluid To Newtonian fluid flow) in this paper. In contrast, Fig. 1b explains the flow situation of the present study, which involves dosing water into the drag-reduced surfactant solution flow from the channel wall. This flow situation was named N2NN (Newtonian fluid To Non-Newtonian fluid flow) in this paper. In this situation, the concentration of the surfactant solution decreases toward the dosing wall (i.e. the injected water exists at a greater concentration near the dosing wall).

To our knowledge, a similar situation to this N2NN flow was previously investigated by direct numerical simulation (DNS) by Yu et al. (2005). They assumed that the Newtonian and non-Newtonian fluids coexist in the drag-reducing channel flow as layers of varying thicknesses. According to their calculations, if the Newtonian fluid exists near the wall in the non-Newtonian drag-reduced flow similar to the N2NN flow situation, the drag reduction rate (DR) decreases as the thickness of the near-wall Newtonian fluid layer increases. The present study realizes this N2NN flow situation experimentally for the first time. It is of great academic worth to investigate the characteristic turbulent structure of the N2NN modified drag-reduced flow. Moreover, by comparing the present study with our previous studies, we can also conduct an analysis of the factors which can affect the skin friction in the drag-reduced turbulent flow.

Against this background, in this study we investigated the characteristic turbulent structure of the N2NN channel flow of viscoelastic fluids by dosing water (Newtonian fluid) from the wall. Particle imaging velocimetry (PIV) measurements were carried out to investigate the near-wall turbulent structure in this modified drag-reduced flow. Planar laser-induced fluorescence (PLIF) measurements were performed to observe the motion of injected fluids in the same flow situation. Finally, the concept of anisotropy of the near-wall turbulence is discussed. The purpose of this study is to examine how a thin layer of Newtonian fluid covering the near-wall region in a viscoelastic drag-reduced flow affects the turbulent structure and drag reduction.

2. Experiment

2.1. Experimental apparatus

Fig. 2 shows a schematic diagram of the experimental apparatus. All the dimensions above are in millimeters (mm). The experiment was performed in a closed-circuit water loop with a two-dimensional channel having a length of 6000 mm, a width of 500 mm and a height of 40 mm ($2h$). The detailed structure of this

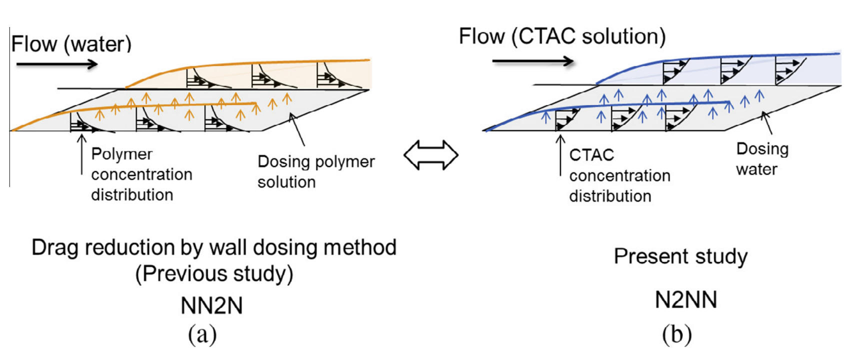

Fig. 1. Conceptual models of the flow situations of (a) NN2N and (b) N2NN.