International Journal of Heat and Fluid Flow 63 (2017) 56–66

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Analysis of an organized turbulent structure using a pattern recognition technique in a drag-reducing surfactant solution flow

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ARTICLE INFO

Article history:
Available online 13 September 2016

Keywords:
Viscoelasticity
Drag reduction
Turbulent flow
Surfactant solution
Pattern recognition technique
PIV

ABSTRACT

This work presents the investigation for an organized turbulent structure in a drag-reducing flow of dilute surfactant solution by utilizing a particle image velocimetry system to perform the pattern recognition technique on a trajectory in four quadrants of streamwise and wall-normal velocity fluctuations. The pattern recognition is added to a new algorithm in order to directly capture the spatial rotation motion. The Reynolds number based on the channel height and bulk mean velocity was set to 1.5×10^4. Surfactant solution with a weight concentration of 150 ppm was employed and the drag reduction rate was 65%. In the drag-reducing flow, we observe increased frequencies of occurrence of the flow events that correspond to a meandering motion in the wall-normal direction of the high-and low-speed regions. Three findings from investigation of the ensemble-averaged Reynolds shear stress and vortex structure are as follows: (i) the Reynolds shear stress in the large fluctuation range occurs in the narrow region; (ii) Size, strength, arrangement and inclination in the spatial vortex structure in the drag-reducing flow differ from those of the water; and (iii) all trajectory contributions for the wall friction coefficient decrease. Finally, we interpreted that the viscoelasticity characterizing the viscoelastic stress and relaxation time in rheological properties of the flow changes specific elementary vortex for the drag-reducing flow, and the trajectories of each flow pattern change drastically.

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1. Introduction

The turbulent state is greatly changed by adding surfactant or water soluble long-chain polymer into the water flow because of the fluid viscoelasticity. The new turbulent state is characterized by a dramatic decrease in the momentum transfer ability. This induces a remarkable decrease in the wall friction, called the Toms effect (Toms, 1948). This drag-reducing effect has a potential of energy saving in industrial applications. In wall-bounded flows, the Toms effect is thought to be induced by large changes in the organized turbulent structure. This organized turbulent structure is known to be important for the turbulent transport of momentum. When an organized turbulent structure appears in wall turbulence, it induces the vigorous momentum exchange spatially, resulting in a dramatic increase of the wall friction. Many researchers (Kasagi et al., 1995; Jiménez and Pinelli, 1999; Adrian, 2007; Eitel-Amor et al., 2015) have investigated the dynamics of coherent structures in Newtonian fluid flows. A deeper understanding of the organized turbulent structure would lead to further benefits on flow-control methods in wall turbulence, which needs information on matters such as the length and strength of the optimal structure for drag reduction. Therefore, the organized turbulent structure in the flow with drag reduced by additives should be studied to clarify the drag-reducing mechanism and to reveal optimal structures for turbulence control.

Recently, the organized turbulent structure in the flow with drag reduced by additives was examined in experimental and numerical investigations combined with proper orthogonal decomposition (POD), which can extract each magnitude of energy corresponding to each POD eigenmode. Cai et al. (2009) studied the drag-reducing flow with particle image velocimetry (PIV). They revealed that additives inhibit the turbulent bursting processes and that the contribution of an organized turbulent structure to the turbulent kinetic energy increases. Wang et al. (2011) also confirmed the inhibition of the energy cascade mechanism and the larger contribution of large-scale structures to the turbulent kinetic energy in direct numerical simulation (DNS). In addition, they reported that the large-scale structures align in the spanwise direction alternately as well-organized clockwise and counterclockwise streamwise swirling motions. Cai et al. (2012) reported that the strength of an organized turbulent structure is weaker than that of the Newtonian flow. Wang et al. (2014) showed that greater viscoelasticity is related to a larger conjunction of fluctuating conformation tensors and their stronger interactions with velocity

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.08.015
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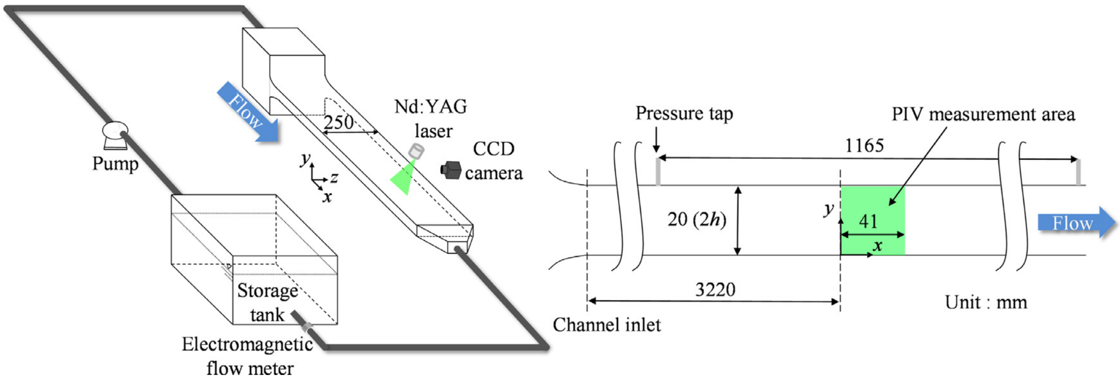

Fig. 1. Shematic diagram of the experimental apparatus. Instantaneous velocity fields in the x-y plane are obtained by a PIV system.

fluctuations. From the previous study with POD, we should acknowledge the existence of the peculiar organized turbulent structure on the large scale, and so there is considerable interest in how this structure is affected by viscoelasticity. As regards the viscoelastic effect on a large-scale vortex, Kim et al. (2013) performed a stress-field analysis with the conditional averages around a hairpin vortex by means of DNS utilizing the finitely extensible nonlinear elastic-Peterlin (FENE-P) model. They revealed that the viscoelastic force acts opposite to the vortex direction and the shape of the hairpin vortex changes in a complex fashion over time under the effect of viscoelastic stress. On the other hand, the disappearance of eddies with the small time scale corresponding to the relaxation time scale, known as the Lumley's time criterion (Lumley, 1969), was confirmed from the experimental result (Warholic et al., 1999a). Here, the relaxation time means the delay time between deformation velocity and stress. These changes of vortex may indicate that the turbulence modulation is induced by viscoelasticity.

In a drag-reducing flow, Li et al. (2004) revealed that the averaged Reynolds shear stress between fluctuations of streamwise velocity and wall-normal velocity (u', v') is equal to zero at each height. This experimental fact indicating the decrease of turbulent transport ability could be explained by a change in the organized turbulent structure. In order to examine the details of relationships between the occurrence of various flow events and an organized turbulent structure, we need a detection method with phase relations between the fluctuating components of velocity due to the turbulent modulation by viscoelasticity, as explained above. Using the detection method, it is important to capture the influence of the viscoelastic stress on the structure and relationships between the Reynolds shear stress and the structure spatially in the velocity field. However, a recent detection method such as involving velocity-vorticity correlation (Chen et al., 2014) is not suitable for the formulation of the organized turbulent structure with phase information in the drag-reducing flow.

In the present study, we utilized a PIV system to measure the turbulent channel flow of a surfactant solution, and extracted a trajectory with phase information in terms of u'-v' phase field using pattern recognition on an organized turbulent structure. This trajectory analysis technique was proposed by Nagano and Tagawa (1995) using data measured by a hot-wire anemometer in the pipe flow. Furthermore, we incorporated the swirling strength into the pattern recognition to find the core of a vortex by extracting the strong rotation motion, as proposed by Zhou et al. (1999). Consequently, we have elucidated the details of the peculiar organized turbulent structure of viscoelastic fluid.

The article is organized as follows. Section 2 describes the experimental set-up, mean parameters based on an estimation of the shear viscosity and procedure of trajectory analysis technique in the PIV measurement. The frequency of occurrence of flow events is presented in Section 3, relationships between Reynolds shear stress and vortex structure are shown in Section 4, and contributions to wall friction coefficient in Section 5 are discussed, by executing the trajectory analysis technique for organized turbulent structures in a drag-reducing flow. Conclusions are presented in Section 6.

2. Procedures of experiment and analysis

2.1. Experimental set-up

A closed-circuit water loop is used for the present study, as shown in Fig. 1. The working fluid flows from a storage tank to a two-dimensional channel and an electromagnetic flow meter, in that order, via pipelines, and impelled by the motive force of a circulating pump. The working fluid temperatures in the storage tank are made constant at 298.2 ± 0.2 K by using a heater and cooling coil. Honeycomb rectifiers are set at the channel entrance to remove large eddies. The two-dimensional channel is made of transparent acrylic resin and the test section is straight with a length of 4530 mm (453 h), a width of 250 mm (25 h), and a height of 20 mm (2h). The electromagnetic flow meter with a precision of ± 0.5% for velocity is installed to calculate the desired bulk mean velocity U_b in the test section. The three-dimensional Cartesian coordinates are also shown in Fig. 1. Throughout the paper, the instant velocity components in the streamwise (x), wall-normal (y) and spanwise (z) directions are u, v and w, respectively.

We use a PIV system to measure instantaneous velocities (u, v) in the (x, y)-plane at a point located 3220 mm (322 h) downstream from the entrance of the channel. At this location, the flow is fully developed. We define the position of the upper edge of the PIV measurement area at $x = 0$. The measurement area is $41 \times 20\ \mathrm{mm}^2$ ($4.1\,\mathrm{h} \times 2.0\,\mathrm{h}$). We employ a double-pulse laser (New Wave Research Co., Ltd., MiniLase-II/30 Hz) constructed of an output of 30 mJ/pulse and a wavelength of 532 nm as the luminary, which is synchronized through the synchronizing equipment with a CCD camera with a resolution of 2048 × 2048. The laser sheet thickness is 0.6 mm, so measurement errors due to light scattering are suppressed. The flow is seeded using nylon particles as the tracer particles, with a mean diameter of 4.1 μm and specific gravity to water of 1.02. The interrogation area is set to 32 × 32 pixels with an overlap of 75% in each direction. Turbulent statistics are calculated based on 500 instantaneous velocity fields and the total vector number is 253 × 128 per frame. Measurement uncertainty for the mean velocity for the water flow is 4.2%, which is estimated according to the Handbook of PIV (Visualization Society of Japan (ed.), 2002). The pressure difference between $x = -26.5$ h and $x = 90$ h is obtained by a precise differential pressure gauge (Sokken, PZ-77) with uncertainty of ± 0.01 $\mathrm{mmH_2O}$ and with data

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