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PIV and DNS analyses of viscoelastic turbulent flows behind a rectangular orifice

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ABSTRACT

We performed PIV (particle image velocimetry) measurements and DNS (direct numerical simulations) on turbulent orifice flows for the Newtonian fluid and viscoelastic fluids, and compared their results with emphasis on turbulence statistics and vortical motions just behind the orifice rib. In the experiment, a cationic surfactant solution of CTAC (cetyltrimethyl ammonium chloride) was chosen as the viscoelastic fluid that is known to provide substantial drag reduction in the case of smooth-wall turbulence. In the viscoelastic flows, the formation of the Kelvin–Helmholtz vortices emanating from the orifice edge was found to be attenuated compared to the Newtonian case, resulting in the suppression of turbulent eddies and Reynolds shear stress behind the orifice. However, the variation of the drag depended on the Reynolds number and the surfactant concentration (or the Weissenberg number): that is, the drag-reducing effect can be achieved only in limited conditions or low Reynolds-number flows. Although DNS results was found to be in qualitative agreement with the experimental data, we discussed also inconsistency between the experimental and DNS results.

1. Introduction

Viscoelastic-fluid flows through complicated geometries are related to practical applications in the field of piping and shipping industries that leverage the phenomena of drag reduction by adding polymer or surfactant to liquid solvent for a purpose of energy saving. It is well known that viscoelastic fluid can cause suppression of turbulence and reduce skin frictional drag, at least, for flows in simple geometries: intensive works have been widely documented and many comprehensive reviews are available (e.g., Virk, 1975; Gyr and Bewersdorff, 1995; Zakin et al., 1998; White and Mungal, 2008; Li et al., 2012). As a recent successful example of applications, Takeuchi (2012) reported a demonstration test, by which drag-reducing surfactant solution was verified to reduce the transfer power of coolant water for air conditioning systems of buildings and 65% of energy conservation was achieved. As it is typical for drag-reduced fluid flow, drag prediction and its control are among the main objectives of studies on the viscoelastic-fluid dynamics. However, the turbulent flow that passes over a bluff body or roughness elements is very complex by the formation of a shedding vortex sheet relating to Kelvin–Helmholtz (K–H) instability and because of its transition to strong turbulence behind the bluff body: see, for example, Makino et al. (2008) and ElKhoury et al. (2010), who examined numerically a orifice flow of the Newtonian fluid. Additionally, the turbulence modulation induced by the fluid elasticity in complex flow geometries is still not well understood. Therefore, turbulent flows over wall roughened by simple geometric elements, such as two-dimensional transverse ribs, continue to be of interest in fluids engineering from several perspectives.

Tsukahara et al. (2011b) performed DNS (direct numerical simulation) of turbulent orifice flows of viscoelastic fluids and reported significant differences in characteristics of turbulence and the mean flow when compared with those of the Newtonian fluid. Since their numerical study was limited in a low Reynolds-number range, a further investigation including an experimental work should be required to estimate practical Reynolds numbers. Poole and Escudier (2004) investigated turbulent sudden-expansion flows of viscoelastic fluids using an LDA (Laser Doppler Anemometer). They found that the wall-normal and spanwise turbulent intensities decreased in a separated shear layer, while the streamwise component increased, suggesting a strongly anisotropic flow even at high Reynolds numbers. It can be conjectured that the suppression of turbulence by the fluid viscoelasticity should have some kind of directivity. However, they could not capture instantaneous turbulent structures in the separated shear layer because of the limitation in single-point measurement of LDA. Ntamba and Fester (2012) determined the pressure-loss coefficients for various orifices in pipe flows of non-Newtonian fluids in both laminar and turbulent flow regimes. They developed an empirical correlation to

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predict it based on their phenomenological analyses. Other than these studies, there are several numerical and experimental works on sudden-expansion flows (e.g., Pak et al., 1990; Castro and Pinho, 1995; Oliveira, 2003; Poole and Escudier, 2003a), a backward-facing step flow (Poole and Escudier, 2003b), and a cavity flow (Liberzon, 2011) owing to their geometrical simplicity. Unfortunately, to the authors' knowledge, there has never been any other DNS study of viscoelastic turbulent flow through complicated geometries (than those carried out by authors' group recently), partly due to numerical difficulty, namely, the Hadamard instability in viscoelastic-flow calculations. From a number of numerical contributions that have been published, we mention here some DNS studies on smooth-wall-bounded flows (e.g., Dimitropoulos et al., 1998; Housiadas and Beris, 2004; Li et al., 2006; Kim et al., 2008; Tamano et al., 2009). They showed that the elongational viscosity and Weissenberg number would be key parameters for the drag reduction in turbulent states. A mechanism of suppression of turbulence has been elucidated in terms of relationships between viscoelastic stress and turbulence structures: many researchers have demonstrated that the viscoelastic (polymer) stress counteracts near-wall streamwise vortices (see, for instance, DeAngelis et al., 2002; Dubief et al., 2004; Li and Graham, 2007; Kim et al., 2008). However, even for a smooth channel, the high Reynolds-number and Weissenberg-number simulations are quite challenging issues and thereby the comparative experiment between DNS and water-channel measurement is still difficult to be done on the drag-reducing turbulence. Recently, Thais et al. (2012) have carried out a moderately high Reynolds-number DNS on the viscoelastic turbulent channel flow at $Re_{\tau 0} = 1000$ (defined later), but which is probably lower than typical level in industrial applications. It must be reasonable to investigate turbulent flows experimentally at high Reynolds numbers, while detailed mechanisms pertaining to fine-scale turbulent structures should be addressed using DNS. Therefore, in the current study we have performed DNS at low Reynolds numbers to obtain a perspective on modulated turbulent structures in viscoelastic fluid flows and have carried out experiments to measure the flow resistance in a wide range of the Reynolds number. One of the motivations for the present work is to provide consistent comparison between numerical and experimental results with respect to viscoelastic turbulent flows over a roughened wall, for a discussion about the streamwise variations of the viscoelastic flow as well as turbulence characteristics.

In this paper, we investigated turbulent viscoelastic fluid flow past orifice by way of experiment and numerical study. As the experiment, we performed PIV (Particle Image Velocimetry) measurements in two different measurement planes in just downstream of single orifice and also pressure-loss measurements to investigate the effect of the orifice on drag reducing channel flow. In the numerical study, we performed DNS on the Newtonian/viscoelastic turbulent flow through multiple rectangular orifices. We compared their results with emphasis on the vortical motions and turbulence statistics.

2. Experimental apparatus, conditions, and measurement procedure

2.1. Water loop and test section

The PIV measurements on turbulent flows past a rectangular orifice were conducted using a closed-circuit water (or surfactant solution as a viscoelastic liquid) channel with a flow section of $L_y \times L_z = 40$ mm $\times$ 500 mm, as schematically illustrated in Fig. 1a. This channel is made of transparent acrylic resin, so that a laser sheet for PIV measurement can be inserted from arbitrary position and we can detect easily undesirable air bubbles affecting the flow if they are trapped in the recirculation around the orifice. For the

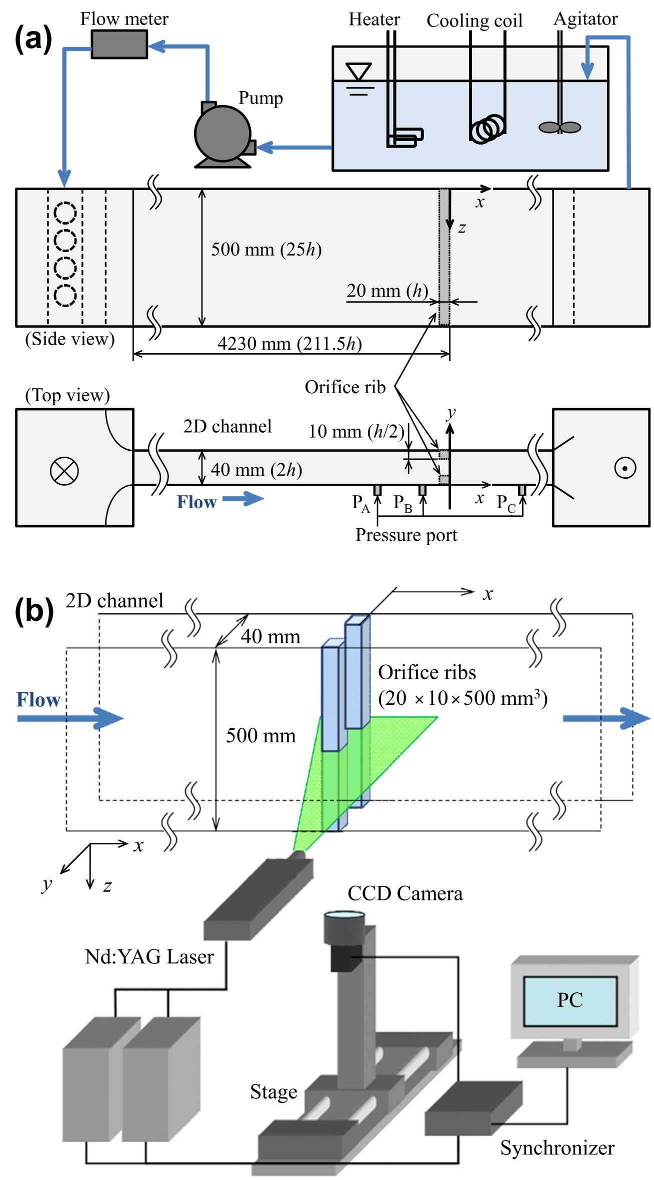

Fig. 1. Outline of experimental apparatus. (a) Closed-circuit water channel flow system, and (b) PIV measurement system.

non-dimensionalization in this paper, we use the channel half width of $h = 20$ mm. A rectangular orifice with 1:2 expansion rate was placed at a distance of more than $200h$ downstream of the contraction inlet and the thickness of each orifice rib was 20 mm: that is, we experimentally demonstrated a fully-developed flow approaching a single pair of two transverse h-by-$h/2$ ribs. The fully-developed state at the place of interest was verified by measurement of a constant mean velocity at a fixed wall-normal distance for several locations in the streamwise direction (i.e., $\partial\langle u\rangle/\partial x \approx 0$, where $\langle\cdot\rangle$ denotes the ensemble average in time) for the smooth channel flow.

In the water circuit, an electromagnetic flow meter with an uncertainty of ± 0.01 m^3/min was installed downstream of the pump for measuring the flow rate. A storage tank was equipped with a heater and an agitator to keep the fluid temperature constant at 25 ± 0.1 °C during the experiment. Two sets of experiments were performed to provide both statistics profiles and vortical structures in instantaneous fields for the tap water (Newtonian fluid) and the surfactant solution (viscoelastic fluid).