International Journal of Heat and Fluid Flow xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Experimental investigation of streamwise velocity fluctuation based on the Reynolds-number dependency in turbulent viscoelastic-fluid flow

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ARTICLE INFO

Keywords:
Turbulent flow
Drag reduction
Reynolds-number dependence
Surfactant solution

ABSTRACT

This paper describes an experimental verification of energy supply mechanisms for the streamwise component of the turbulent kinetic energy (TKE) at different Reynolds numbers in viscoelastic-fluid flow. We investigated the characteristics of the streamwise turbulent velocity fluctuation by analyzing the production and turbulent diffusion terms in the TKE transport equation. In addition, we reported on the Reynolds-number dependency in a high Reynolds-number regime where direct numerical simulation cannot demonstrate changes in fluid properties. Based on the experimental verification, we proposed a conceptual model of the energy-exchange term between the TKE and the elastic energy, with focusing on the dependency of the fluid properties on the shear stress. This model is indirectly reflected in the streamwise TKE, the instantaneous velocity field, and the wave number relevant to energy-containing eddies. The main gain term of the TKE switches between the energy-exchange term and the production term dependently on the Reynolds number: as the Reynolds number exceeds the value which provides the maximum drag reduction rate, the production term becomes dominant and the magnitude of streamwise TKE becomes high compared to the water flow case.

1. Introduction

A practically important effect of drag reduction (DR) can arise in flows of surfactant aqueous solutions. To achieve this effect, a macromolecular aggregation of the surfactant must provide viscoelasticity to the flow. Viscoelastic-fluid flows exhibit a DR rate up to 80% in pipe flows we may frequently encounter in industrial applications. The turbulence in the viscoelastic fluid shows strong anisotropy of turbulent intensity, or the Reynolds normal stresses (Warholic et al., 1999), and exhibits almost zero Reynolds shear stress despite remaining of velocity fluctuations (Li et al., 2006). These features of the anisotropy and the zero Reynolds shear stress imply a difficulty in applying a traditional concept of the turbulent mixing theory. Therefore, this phenomenon accompanied by the DR effect has attracted much attention both from applied and fundamental points of view.

One of the demands for industrial applications of surfactant-induced DR is to elucidate the non-linear relationship between the DR rate and the Reynolds number, which results from the complicated interaction state between the turbulent flow and the macromolecular aggregation. The non-linear relationship makes the determination of the optimum settings for the flow rate in terms of maximum energy savings more difficult before the DR effect is introduced. In fact, a previous experiment demonstrated the wall friction coefficient C_f as a non-linear function of the Reynolds number Re in drag-reducing turbulent channel flows (Motozawa et al., 2011), as shown in Fig. 1. Gyr and Bewersdorff. (1995) also reported on the non-monotonic behavior of C_f in a typical drag-reducing flow, as illustrated in Fig. 2 (we added flow regimes to ensure adequate context for the present study).

A refined Reynolds-Averaged Navier-Stokes (RANS) model should be suitable for understanding a given flow or explicitly predicting a high-efficiency system involving fluid transport. Even for the direct numerical simulation (DNS), there still remains an issue resulting from uncertainties regarding the choice of a rigorous constitutive equation. Fig. 1 includes the DNS results from Yu et al. (2004), Ptasinski et al. (2003), and Tsukahara et al. (2011) for illustrative purposes. In comparison with the previous experimental study (Motozawa et al., 2011), these results reflect different analytical conditions, including the ratio of the longest relaxation time to the viscous timescale, called the friction Weissenberg number We_τ, and that of the solvent viscosity to the total zero-shear viscosity of the solution, β. Therefore, the numerical conditions/results would inevitably not disagree with those of experiments. We may, however, learn the following aspects from DNS studies by several researchers. First, C_f does not have a drastically low value at high Re (i.e., Re $\geq 1.9 \times 10^4$ as in the case of Fig. 1), compared to the maximum drag reduction (MDR) asymptote (Virk, 1975). This is derived from the fact that DNS cannot describe the

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.09.016
Received 1 May 2017; Received in revised form 21 September 2017; Accepted 26 September 2017

Please cite this article as: Hara, S., International Journal of Heat and Fluid Flow (2017), http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.09.016

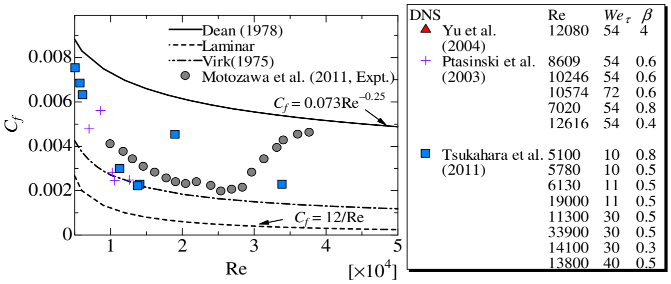

Fig. 1. Wall friction coefficient as a function of the Reynolds number for viscoelastic-fluid flows. This figure shows the results of the experiment and direct numerical simulation with a constitutive equation in previous studies. Motozawa et al. (Experiment (Motozawa et al., 2011)), Yu et al. (Giesekus model)(Yu et al., 2004), Ptasinski et al. (FENE-P model)(Ptasinski et al., 2003), and Tsukahara et al. (Giesekus model) (Tsukahara et al., 2011).

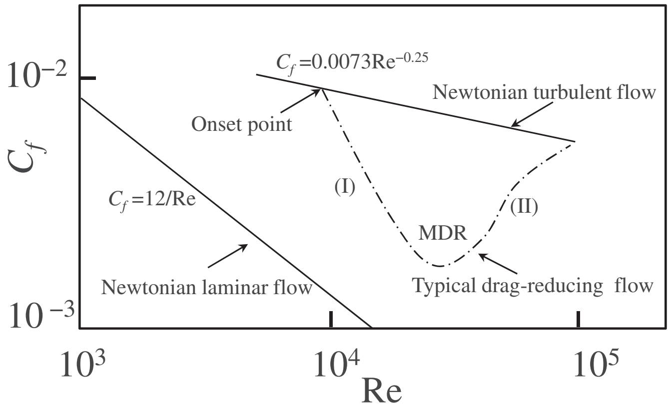

Fig. 2. Reynolds-number dependency of wall friction coefficient in a typical drag-reducing flow.

almost zero mean Reynolds shear stress directly leading to the high DR rate (although we should not exclude the possibility of the inherent Re-dependency of the DR rate). This trend is true not only for the FENE-P model (Bird et al., 1980), but also the Giesekus model (Giesekus, 1982), which can estimate high DR rates, as reported by Dimitropoulos et al. (1998). This implies that the simulated turbulence of the viscoelastic-fluid flow and the ratio of the Reynolds shear stress to the viscoelastic stress appearing in the momentum conservation equation are different from the real values, even though the DR rate estimated from the DNS has the same value as the experimental results. Second, the DNS does not reflect the increasing tendency of C_f in 'the flow regime II', cf. Fig. 2. This can be attributed to the lack in consideration for the disappearance of viscoelasticity that results from changes in the fluid properties dependent on the shear stress (i.e., the breakup of the macromolecular aggregation), which is also interdependent on the growth rate of an instability in the flow field. As mentioned above, the DNS for viscoelastic-fluid turbulent flow does not describe changes in the fluid properties and cannot reproduce the almost zero Reynolds shear stress. Nevertheless, the DNS approach is still a useful tool for turbulent statistical analysis of the near-wall region, the stress field (difficult to be measured in experiment), and the transport equations of the turbulent kinetic energy (TKE). Therefore, we should experimentally examine the viscoelastic-fluid flow based on detailed knowledge from the DNS in order to understand the DR effect.

In the plane channel flow of a viscoelastic fluid, the TKE remains even in MDR state. Thus, examination of the transport equations of TKE is a promising way to understand the DR effect, including the Reynolds shear stress and how modulated turbulence can sustain. In this flow, an additional term appears in the TKE equation, which indicates an energy exchange between the TKE and the elastic energy that is stored in the macromolecular aggregation. This term can be negative or positive depending on the sign of the viscoelastic stress fluctuation and that of the fluctuating velocity gradient. Many researchers have reported the energy-exchange term Λ_{ii} as a sink term, and they have also found an increased root-mean-square (RMS) value of streamwise velocity fluctuations normalized with the inner scale, u'^{+}_{rms} compared to that of a Newtonian fluid (Yu et al., 2004; Ptasinski et al., 2003; Thais et al., 2012; Dimitropoulos et al., 2001). This energy transfer to the elastic energy supports the following phenomenological explanations for the DR effect: the viscous theory (Lumley, 1969) and the elastic theory (Tabor and Gennes, 1986). However, Dallas and Vassilicos (2010) showed different statistical trends for u'^{+}_{rms} and Λ_{ii}, which acts as a positive source of the TKE. Warholic et al. (1999) pointed out that the energy supply from the elastic energy through Λ_{ii}, instead of the zero TKE-production term ($P_{ii} \approx 0$), sustains turbulence. To address this controversy, (Pereira et al., 2017), (Dubief et al., 2004) and (Min et al., 2003) provided interesting conceptual models for the energy transfer between turbulent and elastic energies. These models explain the turbulence-enhancing effect by additives in the near-wall region as well as in the buffer and log layers. An important feature of Λ_{ii} that has not been sufficiently analyzed is its dependence on Re, which must be relevant to onset of the flow regime II (i.e., a weakening of the DR effect). This issue is one of main focuses in this paper.

Hence, it is interesting to investigate distributions of Λ_{ii} including the change in fluid properties and the TKE in different flow regimes. In the present study, we experimentally investigated the dependence of the TKE on the Reynolds number using particle-image-velocimetry (PIV) measurements in a two-dimensional channel flow with surfactant additives. Although Λ_{ii} cannot be measured directly in experiments, we qualitatively discussed the energy supply mechanism through an examination of the energy exchange and production terms in the TKE transport equation, which is based on information acquired from the DNSs of previous studies. In particular, the TKE in the streamwise component $u'u'$ was analyzed with emphasis on the appearance of the production rate in the TKE equation along, in order to confirm the corresponding relationship of near-wall streaks.

2. Experimental set-up and conditions

A closed-circuit water loop illustrated in Fig. 3 was used for this study. The working fluid temperature in the storage tank was held constant at 298.2 ± 0.2 K using a heater and a cooling coil. The two-dimensional channel was made of transparent acrylic resin and the test section was straight with a length of 4530 mm (453h), a spanwise width of 250 mm (25h), and a gap height of 20 mm (2h). An electromagnetic flow meter with a precision of ± 0.5% for velocity was installed to calculate the desired bulk mean velocity U_b in the test section. We used a PIV system to measure instantaneous velocities (u, v) in the (x, y)-plane at a point located 3220 mm (322h) downstream from the channel entrance. Here, the streamwise direction is described as $x_1 = x$ and the wall-normal direction is $x_2 = y$. The instantaneous velocities in the respective directions are u and v. A fully developed velocity profile was ensured at the measurement location.

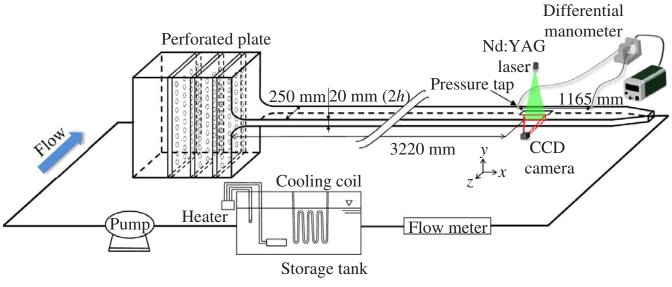

Fig. 3. Schematic overview of the experimental set-up.