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Parametric study of surfactant-induced drag-reduction by DNS

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Abstract

The effect of rheological parameters on the drag-reduction by surfactant additives is studied with a viscoelastic Giesekus model. It is found that the streamwise vorticity becomes much weaker and more elongated with the increase of large drag-reduction rates. The modifications of streamwise vorticity are given. The alteration of the energy cascade process is discussed.

Keywords: Surfactant; DNS; Drag-reduction; Giesekus model; Rheological parameters

1. Introduction

In a previous DNS study (Yu et al., 2004), a viscoelastic Giesekus model (Giesekus, 1982) was adopted to model the interaction between the network structures made up of rod-like micelles and solvent for the simulation of a 75 ppm surfactant solution at Reynolds number of around ten thousand. The numerical results qualitatively agreed with the experimental data, indicating that the Giesekus model is appropriate for surfactant solutions. Experiments showed that surfactant-induced drag-reduction is closely associated the concentration of the solution (Li et al., 1998). This is because the rheological properties vary greatly with the concentration (Kawaguchi et al., 2003). Therefore, it is interesting and necessary to perform a systematic investigation to study the effect of rheological properties on the turbulence structures and drag-reduction rate to further clarify the turbulent transport mechanism in drag-reducing flow. To develop a viscoelastic model for engineering applications, we need to establish a DNS database covering a wide range of rheological properties. For these scientific and engineering reasons, we carried out a series of runs for the surfactant solution with a faithful finite difference scheme (Yu and Kawaguchi, 2004) for a fully developed channel flow.

2. Numerical method

The drag-reduction by surfactant additives is related to the elasticity of the network structures formed by the rod-like micelles in the solution (Yu et al., 2004). We employed a viscoelastic Giesekus constitutive equation to model the interaction between the elastic network structures and solvent. The dimensionless governing equations for a fully developed turbulent channel flow can be written as

$$\frac{\partial u_i^+}{\partial x_i^*} = 0 \tag{1}$$

$$\frac{\partial u_i^+}{\partial t^*} + u_j^+ \frac{\partial u_i^+}{\partial x_j^*} = -\frac{\partial p^+}{\partial x_i^*} + \frac{\beta}{Re_\tau}\frac{\partial}{\partial x_j^*}\left(\frac{\partial u_i^+}{\partial x_j^*}\right) + \frac{1-\beta}{We_\tau}\frac{\partial c_{ij}^+}{\partial x_j^*} + \delta_{1i} \tag{2}$$

$$\frac{\partial c_{ij}^+}{\partial t^*} + \frac{\partial u_{\mathrm{m}}^+ c_{ij}^+}{\partial x_{\mathrm{m}}^*} - \frac{\partial u_i^+}{\partial x_{\mathrm{m}}^*} c_{mj}^+ - \frac{\partial u_j^+}{\partial x_{\mathrm{m}}^*} c_{mi}^+ + \frac{Re_\tau}{We_\tau} [c_{ij}^+ + \alpha(c_{im}^+ - \delta_{im})(c_{mj}^+ - \delta_{mj}) - \delta_{ij}] = 0 \tag{3}$$

where c_{ij}^+ is the conformation tensor associated with the deformation of the network structures. Re_τ ($Re_\tau = \rho U_\tau h/$

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Nomenclature

c	conformation tensor
C	mean conformation tensor
DR*%	drag-reduction rate (the reduction of friction factor with respect to Newtonian fluid at equal mean Reynolds number Re^*_m)
E	elastic energy $= \frac{1}{2}\frac{\eta}{\lambda}tr(c)$
f	friction factor $= 2\tau_w/\rho U_b^2$
h	half height of the channel
$\overline{k_e}$	mean elastic energy of the network structures over space and time
p	pressure
Re^*_m	Reynolds number $= 2\rho U_b h/\eta_w$
Re_τ	Reynolds number $= \rho U_\tau h/\eta_0$
Re^*_τ	Reynolds number $= \rho U_\tau h/\eta_w$
t	time
u	velocity
$\overline{u^+_{rms}}$	average root-mean-square of the streamwise velocity over space and time
$\overline{v^+_{rms}}$	average root-mean-square of the wall-normal velocity over space and time
$\overline{w^+_{rms}}$	average root-mean-square of the spanwise velocity over space and time
U	mean velocity
U_b	mean bulk velocity
U_τ	friction velocity $= \sqrt{\tau_w/\rho}$
$-\overline{u'^+v'^+}$	Reynolds shear stress
We_τ	Weissenberg number $= \rho\lambda U_\tau^2/\eta_0$
x	spatial coordinate
y^*	dimensionless coordinate $= y/h$
y^+	$= y^* \times Re_\tau$
y^{+*}	$= y^* \times Re^*_\tau$

Greek symbols

α	mobility factor
β	ratio $= \frac{\eta_s}{\eta_0}$
δ^{+*}_{urms}	peak value position of the RMS of the streamwise velocity fluctuation base on the effective viscosity at the wall η_w
$\overline{v_t}$	the mean turbulent viscosity over space and time
ϖ	vorticity
η_a	dynamic shear viscosity of surfactant contribution
η_s	dynamic shear viscosity of solvent contribution
η_0	viscosity of the surfactant solution at zero-shear rate
η_w	the effective viscosity at the wall
λ	relaxation time

η_0) is the frictional Reynolds number based on the frictional velocity, half of the channel height and zero-shear rate viscosity. We_τ ($We_\tau = \rho\lambda U_\tau^2/\eta_0$) is Weissenberg number. Mobility factor α is a key parameter in determining the extensional viscosity. β is the ratio of solvent viscosity η_s over the zero-shear rate solution viscosity η_0 ($\eta_0 = \eta_a + \eta_s$, η_a is the contribution of surfactant additive).

The various rheological parameters shown in Table 1 are investigated to identify their effects on drag-reduction with a fixed Reynolds number, $Re_\tau = 150$. Dimitropoulos et al. (1998) studied the effect of the variation of rheological parameters with a Giesekus model. Their studies were for dilute solutions with β no more than 0.9 and the maximum drag-reduction rate was 44%. In order to get a larger drag-reduction rate, smaller β values are adopted in this study. The numerical method used here is a fractional-step method. The Adams–Bashforth scheme is used for time-advancement to ensure second-order accuracy in time. The second-order faithful finite difference scheme of Yu and Kawaguchi (2004) is used to enhance the numerical stability.

3. Results and discussion

The Reynolds number based on the effective viscosity, $\eta_w = \eta_0(\beta \mathrm{d}U^+/\mathrm{d}y^+ + (1-\beta)C^+_{xy}/We_\tau)/(\mathrm{d}U^+/\mathrm{d}y^+)$, at the wall is used for data reduction (Sureshkumar et al., 1997). The drag-reduction (DR) rate is defined as the reduction of the friction factor with respect to a Newtonian fluid at an equal mean Reynolds number, where the frictional factors of Newtonian fluid are evaluated by Dean's equation (Dean, 1978).

Some important results are listed in Tables 1 and 2. Table 1 shows that the DR rate increases with the increase of We_τ, with the decrease of α and with the decrease of β. Fig. 1 shows the velocity profiles. All the velocity profiles collapse in the viscous sublayer, and the velocity profile upshifts further in the bulk flow region with the increase of DR rate. Table 2 shows that generally speaking, larger DR rates are associated with larger $\overline{u^+_{rms}}$, smaller $\overline{v^+_{rms}}$ and

Table 1
Computational parameters and some important results

Fluid	β	We_τ	α	η_0/η_w	U^+_m	Re^*_τ	Re^*_m	DR*%
A	0.5	8	0.001	1.107	15.08	166	5000	0
B	0.5	12.5	0.001	1.184	18.14	178	6440	25.4
C	0.5	20.0	0.001	1.311	22.14	197	8710	46.0
D	0.5	30.0	0.001	1.455	25.92	218	11300	57.9
E	0.5	40.0	0.001	1.533	30.36	230	13970	67.7
F	0.5	50.0	0.001	1.598	33.32	240	15980	72.0
G	0.5	20.0	0.01	1.668	22.33	250	11180	43.5
H	0.3	30.0	0.001	1.907	29.15	286	16670	63.4
I	0.8	30.0	0.001	1.126	22.06	169	7450	46.3
N	–	–	–	1.000	14.78	150	4440	–

*Based on η_w. A–I denote viscoelastic fluids and N denotes Newtonian fluid.