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DNS study on heat transfer of viscoelastic decaying isotropic turbulence

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ABSTRACT

Direct numerical simulation (DNS) on viscoelastic decaying isotropic turbulence was carried out to investigate heat transfer reduction (HTR) mechanism. The transport equations of thermal fluctuation energy and heat flux were derived in both physical space and Fourier space. The effects of viscoelasticity on the transport equations were studied to analyze the mechanism of thermal fluctuation reduction and HTR. Statistics and Fourier space distributions of turbulent kinetic energy, thermal fluctuation energy, and turbulent heat flux of viscoelastic fluid were presented, and compared with those in Newtonian fluid. The effects of viscoelasticity on turbulent and thermal fluctuations were illustrated intuitively via curvelet method.

1. Introduction

Since Toms effect (Toms, 1948) was discovered, technology of turbulent drag reduction (DR) by additives has attracted great attention, due to its notable energy saving for fluid transport. Studies have shown that turbulent heat transfer was also reduced due to the viscoelasticity of drag-reducing fluid along with DR phenomenon. This can be a disadvantage in some applications of DR technology. For instance, for district heating and cooling systems (DHC), the viscoelasticity can affect the heat exchange efficiency of the system seriously. However, for long-distance pipeline heating transportation of high-viscosity crude oil, viscoelasticity can not only reduce the resistance of crude oil pipeline transportation but also weaken the heat transfer to reduce its viscosity. Anyhow, it is of great significance to investigate the HTR mechanism in order to avoid or make full use of this reduction, effectively.

The early-stage studies (Kale, 1977; Pruitt et al., 1966; Wells, 1968; Corman, 1970; Meyer, 1966; Poreh and Paz, 1968) on HTR phenomenon were mainly to establish the empirical formulas of the heat transfer coefficient. Cho (Cho and Harnett, 1982) reviewed these formulas and found that many formulas were based on Colburn analogy correlation (Hsu, 1974) of Newtonian fluid, with a modification of the empirical constants or introducing a simple correction factor. However, the relative errors produced by these formulas are usually very large, even up to 30%, and their scopes of application are limited. The Colburn analogy correlation describes the relation between heat transfer coefficient and frictional resistance coefficient. It is based on the famous Reynolds analogy (Tennekes and Lumley, 1972), which assumes the eddy diffusivities for momentum and heat are approximately equal for Newtonian fluid. However, experimental results (Ng et al., 1980; Marrucci and Astarita, 2002; Mizushina and Usui, 1977) indicated that the HTR rate of viscoelastic fluid was always higher than the DR rate. In addition, frictional resistance coefficient and heat transfer coefficient usually do not reach the asymptotic region at the same time. These phenomena indicated that viscoelasticity has different effects on momentum diffusion and thermal diffusion, and Reynolds analogy is no longer valid for viscoelastic fluids (Cho and Harnett, 1982; Matthys, 1991; F.C. Li et al., 2004). That is to say, these empirical formulas cannot accurately predict the heat transfer coefficient. Due to the departure of Reynolds approximation, the research of HTR mechanism has attracted much more attention, and the research group of Kawaguchi has done a lot of work in this field (F.C. Li et al., 2004, Kawaguchi et al., 1997; F.C. Li et al., 2004, Li et al., 2005; Yu and Kawaguchi, 2005). By studying thermal diffusion characteristics of turbulent boundary layer,

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Nomenclature

$\boldsymbol{u}$	velocity fluctuation vector
t	time
$\boldsymbol{x}$	unit vector in physical space
$\boldsymbol{T}^{[s]}$	viscous stress $= \rho \upsilon^{[s]}(\Gamma_{ij} + \Gamma_{ji})$
p	pressure fluctuation
G	uniform temperature gradient
$\boldsymbol{T}^{[a]}$	elastic stress $= (\rho \upsilon^{[a]}/\tau_a)(f(r)\ \boldsymbol{C}\text{-}\boldsymbol{I})$
$\boldsymbol{C}$	conformation tensor
$\boldsymbol{I}$	unit tensor
$f(r)$	Peterlin function $= (L^2\text{-}3)/(L^2\text{-}r^2)$
L	maximum possible extension of drag-reducing additive microstructures
r	extension length of drag-reducing additive microstructures $= \mathrm{trace}(\boldsymbol{C})^{0.5}$
$\boldsymbol{k}$	wave-number vector
k	norm of wave-number vector $= \lvert\boldsymbol{k}\rvert$
$A(k)$	spherical area with a radius of k in spectrum space
$\boldsymbol{e}$	unit vector of Fourier space
Wi	Weissenberg number $= \tau_a(\varepsilon_k/\ \upsilon^{[s]})^{0.5}$
Re_λ	Reynolds number based on Taylor micro scale $= u_{rms}\lambda/\upsilon^{[s]}$
c_p	specific heat at constant pressure
Greek symbols	
Γ_{ij}	velocity gradient
ρ	density
θ	thermal fluctuation
$\upsilon^{[s]}$	kinetic viscosity of solvent
$\upsilon^{[a]}$	kinetic viscosity of solute
β	the ratio of viscosity for solvent to zero shear viscosity for solution $= \upsilon^{[s]}/(\upsilon^{[s]} + \upsilon^{[a]})$
τ_a	relaxation time of viscoelastic solution
κ	thermal diffusion rate
λ	Taylor micro scale for turbulent
ε	dissipation rate
ξ	energy
Superscripts and subscripts	
k	turbulent kinetic
e	elastic
θ	thermal
h	heat transfer
$[s]$	solvent
$[a]$	additive
^	corresponding variables in Fourier space
$< \cdot >$	spatial averaging
$()^*$	conjugate complex

Kawaguchi (Kawaguchi et al., 1997) found that the thermal fluctuations are attributed to three parts: the low-frequency fluctuations in the near wall region, the intermittency of thermal fluctuations at the edge of the thermal boundary layer and the high-frequency fluctuations outside the thermal boundary layer. Li et al. (F.C. Li et al., 2004, Li et al., 2005) made a significant research to study the mechanism of turbulent heat transfer in viscoelastic fluid by simultaneously measuring the turbulent fluctuations and thermal fluctuations in viscoelastic channel flows for the first time via a fine-wire thermocouple probe and laser-Doppler velocimetry (LDV). It is observed from these studies above that due to the viscoelasticity, the eddy diffusivities for momentum and heat all decreased, and the buffer layer in the thermal boundary layer was thickened. The thermal fluctuation spectrum of the measured points in the near wall region shows that the viscoelasticity enhances the large-scale thermal fluctuations and weakens the small-scale thermal fluctuations. In addition, the decrease of correlation between the normal turbulent fluctuation and the thermal fluctuation and the inhibition of turbulent flow leads to the weakening of wall-normal turbulent heat transfer. Yu et al. (Yu and Kawaguchi, 2005) used the two-order MINMOD scheme to discretize the convection terms of Giesekus model, and simulated heat transfer of the fully developed turbulent channel flow for the first time. The results reproduced many of the experimental phenomena, and budget equations of the turbulent heat flux were analyzed. It stated that viscoelasticity weakened the magnitudes of the budget terms in the streamwise and wall-normal turbulent heat fluxes, and the total contribution of the additives acted as a weak sink term except in the vicinity of the wall in the budget of the streamwise turbulent heat flux and as a large sink term in the budget of the wall-normal heat flux. The experiments and simulations deepened the understanding of the viscoelastic fluid heat transfer reduction. But the viscoelastic fluid heat transfer coefficient still can't be predicted and the relationship between heat transfer coefficient and frictional resistance coefficient is uncertain, the HTR mechanism needs further study.

At present, studies of DR and HTR mechanisms mainly concentrate on wall turbulence like channel and pipeline flows. However, the wall effect and induced inhomogeneity and anisotropy hinder deep investigation of the effects of viscoelasticity on momentum diffusion and thermal diffusion (White and Mungal, 2008). There have been some DR studies on viscoelastic isotropic turbulence (Den Toonder et al., 1997; De Angelis et al., 2002; De Angelis et al., 2005; Vaithianathan and Collins, 2003; Kalelkar et al., 2005; Perlekar et al., 2006; Berti et al., 2006; Jin, 2007; Cai et al., 2010; Cai et al., 2012; Feng-Chen et al., 2012). It was found that for viscoelastic turbulence, small-scale turbulent structures were suppressed, the turbulent kinetic energy spectrum distribution and the classical Kolmogorov-type energy cascade were modified significantly, and turbulent dissipation was also depressed. These studies broaden the understanding of DR mechanism. However, the existence of drag reduction in isotropic turbulence still remains controversial (Wei-Hua et al., 2011). There is still no report about HTR phenomenon in viscoelastic isotropic turbulence.

Based on the above review and analysis, the influence of viscoelasticity on heat transfer is investigated by DNS on the heat transfer of viscoelastic isotropic turbulence in this paper. In the second section, the governing equations, the calculation methodology and some numerical details are given. The results are shown in the third section. Spectral distributions and statistical evolutions for turbulent fluctuations, thermal fluctuations and turbulent heat flux of viscoelastic fluid and Newtonian fluid are compared. The transport equations of thermal fluctuations and turbulent heat flux are derived. Then, the influence of viscoelasticity on the terms of the equations is analyzed. At last, conclusions are shown in the fourth section.

2. Governing equations and methodology

In this paper, the HTR mechanism is studied through the viscoelastic decaying isotropic turbulence, and the widely used finitely extensible nonlinear elastic Peterlin (FENE-P) model (Peterlin, 1966) is adopted to calculate the additional elastic stress. The governing equations are:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot \boldsymbol{T}^{[s]} + \frac{1}{\rho}\nabla \cdot \boldsymbol{T}^{[a]} \tag{2}$$

$$\frac{\partial \boldsymbol{C}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{C} = \boldsymbol{C} \cdot \nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T \cdot \boldsymbol{C} - \frac{f(r)\boldsymbol{C} - I}{\tau_a} \tag{3}$$