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A RANS model for heat transfer reduction in viscoelastic turbulent flow

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ABSTRACT

Direct numerical simulations (DNS) were carried out to investigate turbulent heat transfer in a channel flow of homogenous polymer solutions described by the Finitely Extensible Nonlinear Elastic-Peterlin (FENE-P) constitutive model at intermediate and high Prandtl numbers ($Pr = 1.25$ and 5). Time-averaged statistics of temperature fluctuations, turbulent heat fluxes, thermal turbulent diffusivity, and of budget terms of the temperature variance are reported and compared with those of the Newtonian fluid cases at the same Prandtl and Reynolds numbers. Moreover, twenty one sets of DNS data of fluid flow are utilized to improve existing k–ε–$\overline{v^2}$–f models for FENE-P fluids to deal with turbulent flow of dilute polymer solutions up to the high drag reduction regime; specifically the dependency of closures on the wall friction velocity is removed. Furthermore, five sets of recent DNS data of fluid flow and heat transfer of FENE-P fluids were used to develop the first RANS model capable of predicting the heat transfer rates in viscoelastic turbulent flows. In this model, an existing closure for calculating the turbulent Prandtl number for Newtonian fluids is extended to deal with heat transfer in turbulent viscoelastic fluids. Predicted polymer stresses, velocity profiles, mean temperature profiles, and turbulent flow characteristics are all in good agreement with the DNS data, and show improvement over previous RANS models.

1. Introduction

Drag reduction by addition of polymer molecules to the turbulent flow has been extensively investigated both experimentally and numerically over the last decades; comprehensive early reviews on the subject are those of Hoyt [1], Lumley [2] and Virk [3]. From the outset it was observed that the addition of small amounts of high molecular weight linear polymers, such as polyethylene oxide (PEO) or polyacrylamide among others, to low viscosity Newtonian solvents flowing in turbulent pipe or channel flow would reduce drag by up to 80%.

Recent comprehensive theories on the mechanisms of drag reduction induced by polymer additives have been put forward in the literature [4,5]. The mechanism is based on the fact that polymer molecules undergo a coil-to-stretch transition, causing an increase in the extensional viscosity of the solution that helps suppress Reynolds stress-producing events.

Over the last two decades, the development of accurate and efficient numerical and experimental methods for viscoelastic fluids has made it possible to investigate in detail turbulent DR in dilute polymer solutions [6–12]. Most of the numerical simulations used constitutive equations based on the FENE-P (Finitely Extensible Nonlinear Elastic with Peterlin closure) rheological constitutive equation which allows one to probe the effects on the flow of the polymer relaxation time, chain extensibility and of the ratio of polymer to solution viscosities. In this constitutive equation, a polymer chain is represented by a single dumbbell consisting of two beads, representing the hydrodynamic resistance, connected by a finitely extensible entropic spring.

Direct numerical simulations (DNS) of polymer induced drag reduction in turbulent channel flows up to the maximum drag reduction (MDR) limit were carried out using a fully spectral method by Ptasinski et al. [7], Dubief et al. [8], Dimitropoulos et al. [9], Thais et al. [10,11] and Li et al. [12]. They showed that to obtain significant levels of drag reduction large polymer chain extensibilities and high Weissenberg numbers are required. In addition, they studied the influence of rheological parameters of the FENE-P model on the amount of polymer-induced drag reduction.

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Nomenclature

Symbol	Description
C	Conformation tensor
C_p	Specific heat capacity
Ep	Viscoelastic contribution of dissipation equation
$f(C_{kk})$	Peterlin function ($f(c_{kk}) = (L^2 - 3)/(L^2 - c_{kk})$)
$f(L^2)$	Peterlin function for the polymer maximum length ($f(L^2) = 1$)
f	Redistribution function
h	Half width of the channel ($h = 1$)
H^*	Hookean dumbbell spring constant
κ	Isotropic artificial numerical diffusivity constant
k	Turbulent kinetic energy
K	Thermal conductivity
L_t	Turbulence length scale
L^2	Polymer maximum extension length
M	Mean flow distortion term of conformation tensor
S	Rate of strain tensor
P_k	Turbulence production
Pe_t	Turbulent Peclet number ($Pe_t = v_T Pr/v$)
Pr	Molecular Prandtl number
Pr_t	Turbulent Prandtl number
$Pr_{t,extended}$	Extended turbulent Prandtl number
q''	Wall heat flux
$Re_{\tau 0}$	Reynolds number based on friction velocity ($Re_{\tau 0} = hU_\tau/v_0$)
u_i	Velocity vector
T	Instantaneous temperature
T^*	Friction temperature
T_t	Turbulence time scale
$Wi_{\tau 0}$	Weissenberg number based on friction velocity ($Wi_{\tau 0} = \lambda U_\tau^2/v_0$)
U_τ	Friction velocity
x, y, z	Coordinates in streamwise, wall-normal and spanwise directions, respectively

Greek symbols

α_t	Turbulent thermal diffusivity ($\alpha_t = v_t/Pr_t$)
β	Ratio between the solvent viscosity and the viscosity of the solution
ε	Dissipation rate of turbulence
ε_p	Viscoelastic stress work
η_p	Polymer viscosity coefficient
η_s	Solvent viscosity coefficient
v_T	Turbulent viscosity
$v_{T,P}$	Viscoelastic turbulent viscosity
λ	Polymer relaxation time
θ^+	Normalized instantaneous temperature by friction temperature
Θ^+	Reynolds averaged temperature normalized by friction temperature
ρ	Density
δ_{ij}	Kronecker delta

List of abbreviations

DR	Drag reduction
HDR	High drag reduction
IDR	Intermediate drag reduction
LDR	Low drag reduction
NLT	Nonlinear term in time averaged conformation tensor

Passive scalar transport in turbulent channel flow of viscoelastic dilute polymer solutions has been much less studied using direct numerical simulations, but nevertheless an investigation for DR of up to 74% was carried out by Gupta et al. [13]. They showed that DR is accompanied by increased coherence of the low-speed streaks in the buffer layer and that they are responsible for the streamwise heat transport, which is actually enhanced relative to the corresponding flux for Newtonian flow. Simultaneously the wall-normal and spanwise heat fluxes decrease with DR very much as happens with the Reynolds shear stress and the root mean square fluctuations in the wall-normal and spanwise directions. The enhanced anisotropy of the scalar heat fluxes, and in particular the enhancement of the streamwise heat flux, are rather unexpected results, whereas the reduced flow-normal heat flux was somewhat expected.

Yu et al. [14] carried out DNS of fully developed turbulent heat transfer of a viscoelastic drag-reducing flow described by Giesekus model at low Prandtl number ($Pr = 0.71$) and reported turbulent thermal statistics such as temperature fluctuations, turbulent heat fluxes and budget terms of the temperature variance and compared with those of a Newtonian fluid flow.

DNS simulation of turbulent viscoelastic flow is significantly more expensive than Newtonian DNS [12,15]. Hence, Reynolds-Averaged Navier–Stokes (RANS) [15–19], and Large Eddy Simulation (LES) models [21,22] have been developed over the years.

In the context of k–ε turbulence models for viscoelastic fluids Pinho et al. [16], and subsequently Resende et al. [17] proposed closures for Reynolds stresses of viscoelastic fluids described by the FENE-P model that relied on *a priori* analyses of DNS data. In these works Reynolds averaged flow and conformation quantities were predicted well, but both models were limited to applications in the low DR regime (DR < 34%). In addition both models rely on overly complex viscoelastic closures, they do not cover the whole range of drag reduction and do not deal easily with simulations in complex geometries, since they rely on the friction velocity instead of relying exclusively on local quantities for generality.

More recently Takahiro et al. [18] proposed a low Reynolds number k–ε model for viscoelastic fluids described by the Giesekus constitutive equation. Their closure is valid up to the maximum DR. In their proposal, an extra damping function was added to the closure of eddy viscosity, while the treatment of the turbulent kinetic energy (k) and its dissipation rate (ε) is an extension of their adopted base model for Newtonian fluids.

The first turbulence model of first order to be capable of predicting turbulent viscoelastic flows in the high drag reduction regime was developed by Iaccarino et al. [19] in the context of k–ε–$\overline{v^2}$–f model. Their model is based on a simplified representation of the polymer conformation tensor; in particular, they only consider the extension of the chains as characterized by the trace of the conformation tensor. They used the concept of turbulent polymer viscosity to account for the combined effects of turbulence and viscoelasticity on the momentum and conformation equations. Their closure for turbulent polymer viscosity depends on the turbulent kinetic energy, the polymer relaxation time and the trace of conformation tensor and the model of the nonlinear terms in the conformation tensor equation relied on the turbulent dissipation rate. However, although their model predicts accurately the amount of drag reduction, their predictions of the polymer shear stress, of the budget of the turbulent kinetic energy and of the various contributions to the evolution equation for the conformation tensor are not in agreement with DNS results.