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Transient aspects of drag reducing plane Couette flows

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ABSTRACT

The addition of a small amount of polymers of high molecular weight can lead to a decrease in the pressure drop in turbulent flows. Over the years, numerous studies have been conducted in attempts to make practical use of polymer-induced drag reduction. However, many aspects concerning its main mechanism are still unclear. One of those aspects is the development of the turbulent structures and polymer deformation over time in the beginning of the phenomenon. As an attempt to further understand the drag reduction over this developing time, we analyse a turbulent Couette flow of a FENE-P fluid with the aid of direct numerical simulations. We show that the initial interactions between the mean shear flow, turbulent structures, and polymer stretching are the key to understanding the step-by-step evolution of the drag reduction (DR). A few instants after the beginning of the simulation, the DR assumes a significantly negative value before starting to increase and reaches its maximum. When the DR is a minimum, the polymers experience their highest deformation state. The energy necessary to initially stretch them comes mainly from the mean shear flow, which causes a decrease of the DR until its minimum and negative value. After this point, the polymers start to strongly interact with the turbulent structures, which are partially suppressed, and the DR starts to increase. Part of the energy stored by the molecules is then released to the mean flow, increasing the DR to a maximum level while the polymer extension decreases. Lastly, DR reduces, reaching an asymptotic and positive value, which indicates the beginning of the statistical steady flow state.

1. Introduction

The drag reducing flows by polymers has been analysed since the pioneering works of Forrest and Grierson [12], Toms [33] and Mysels [21]. Among its applications there is a great variety of processes, such as fire-fighting operations, transport of liquids in pipes, transport overseas, blood flow resistance, and many others [3,6,11,13,24]. The fundamentals of drag reduction (DR) together with many of its practical aspects can be found in [19,20,28,34,35]. From these papers one can mainly understand how the concentration, molecular weight, and temperature affect the DR.

Phenomenological explanations for polymeric drag reduction gravitate around two major ideas: the viscous theory, independently proposed by Lumley [19] and Seyer and Metzner [25], and the elastic theory postulated by Tabor and de Gennes [28]. Additional details regarding the DR mechanism have also been reported by Dubief et al. [10], Dimitropoulos et al. [8] and Thais et al.[31].

An aspect of DR that has not been sufficiently analysed is its dependence on time, which is particularly significant at the begging of the phenomenon and will be the main focus of this paper. When polymers are introduced into a fully developed turbulent flow, they cause an abrupt disturbance. The mean shear flow and the turbulent structures are strongly changed and a new steady state takes time to be reached, as numerically shown by Dimitropoulos et al. [8] and Tamano et al. [29] and experimentally confirmed by Andrade et al. [2]. The level of drag reduction can even assume negative values at the very beginning of the phenomenon (when the polymers are injected into a turbulent flow, for example). In fact, DR is zero at the beginning and decreases until a minimum value, before starting to increase and achieve its maximum value after a significant period, called the *developing time* [22,23]. The details concerning the polymer–turbulence interactions during this period remain, however, unclear.

Despite the fact that DR has been widely studied, its transient aspect has not not yet been systematically investigated. The focus of our paper is to carefully analyse, with the aid of a numerical

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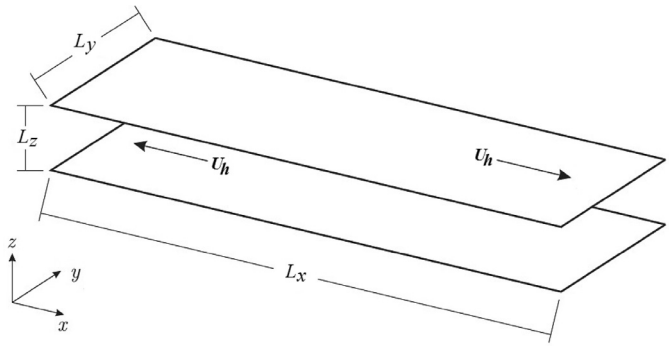

Fig. 1. Geometry of the plane Couette flow with coordinate system.

simulation of a FENE-P fluid, the transient aspects of drag reducing plane Couette flows during the developing time. The initial interactions between the polymers and the flow are fundamental to fully understanding the variations in the level of the drag reduction, which can even assume negative values at the beginning of the simulations. The evolution of DR over time is confronted here with the evolution of the polymer stretching and turbulent structures. In addition, we also analyse the total kinetic energy budget, which is quite a good tool to further understand polymer–turbulence interactions. We believe that the comprehension of these interactions is the key to understanding the DR mechanism.

This paper is organized as follows. In Section 2, we present the physical formulation employed in our simulations. The details concerning our numerical methodology are exposited in Section 3. Following the description of the methodology, our main results are finally presented in Section 4, where the transient aspects of drag reduction are analysed.

2. Physical formulation

A turbulent plane Couette flow of an incompressible dilute polymer solution is considered. Such a geometry represents one of the canonical ones and is commonly adopted in direct numerical simulations due its simplicity as well as its attractiveness for theoretical studies of near wall turbulent interactions.

Here, the plane Couette streamwise direction is $x_1 = x$, the spanwise direction is $x_2 = y$, and the wall-normal direction is $x_3 = z$. The flow is driven by both the top and the bottom plates, which have the same magnitude of velocity in the streamwise direction (U_h) but opposite senses, as shown in Fig. 1. The instantaneous velocity field in the respective directions is $(u_x, u_y, u_z) = (u_1, u_2, u_3)$. In order to conduct a comparative analysis of the inner layer dynamics of the plane Couette flow, wall scaling is used and based on zero-shear rate variables with the length and time scaled by ν_{tot}/u_τ and ν_{tot}/u_τ^2, where $\nu_{tot} = \nu_N + \nu_{p0}$ is the total (solvent + polymer) zero-shear viscosity, and u_τ is the zero-shear friction velocity. Using this scaling, the dimensionless conservation equations are

$$\frac{\partial u_j^+}{\partial x_j^+} = 0, \tag{1}$$

$$\frac{\partial u_i^+}{\partial t^+} + u_j^+ \frac{\partial u_i^+}{\partial x_j^+} = -\frac{\partial p^+}{\partial x_i^+} + \beta_0 \frac{\partial^2 u_i^+}{\partial x_j^{+2}} + \frac{\partial \Xi_{ij}^+}{\partial x_j^+}. \tag{2}$$

In Eq. 2, the superscript '+' indicates the wall unit normalization, p^+ is the pressure, β_0 is the ratio of the Newtonian solvent viscosity (ν_N) to the total zero-shear viscosity (ν_{tot}). The extra-stress tensor components are denoted by Ξ_{ij}^+. The formalism of Eq. 2 includes the assumption of a uniform polymer concentration which is governed by the viscosity ratio β_0, where $\beta_0 = 1$ yields the limiting behaviour of the Newtonian case.

The extra-stress tensor components (Ξ_{ij}^+) in Eq. 2 represent the polymer's contribution to the tension of the solution. This contribution is accounted for by a single spring-dumbbell model. We employ here the FENE-P kinetic theory [5], which is the most preferred one due to its physically realistic finite extensibility of the polymer molecules and to its relatively simple second-order closure. This model employs the phase-averaged conformation tensor $C_{ij} = \langle q_i q_j \rangle$, where the q_i are the components of the *end-to-end vector* of each individual polymer molecule. The extra-stress tensor is then

$$\Xi_{ij}^+ = \alpha_0 (f\{tr(\boldsymbol{C})\} C_{ij} - \delta_{ij}), \tag{3}$$

where $\alpha_0 = (1 - \beta_0)/Wi_{\tau 0}$, and with $Wi_{\tau 0} = \lambda u_\tau^2/\nu_{tot}$ the friction Weissenberg number representing the ratio of the elastic relaxation time (λ) to the viscous timescale. Additionally, δ_{ij} is the Kronecker's delta and $f\{tr(\boldsymbol{C})\}$ is given by the Peterlin approximation

$$f\{tr(\boldsymbol{C})\} = \frac{L^2 - 3}{L^2 - tr(\boldsymbol{C})}, \tag{4}$$

where L is the maximum polymer molecule extensibility and $\{tr(.)\}$ represents the trace operator. This system of equations is closed with an evolution equation for the conformation tensor

$$\frac{DC_{ij}}{Dt^+} = \left(C_{ik} S_{kj}^+ + S_{ik}^+ C_{kj}\right) - \left(C_{ik} W_{kj}^+ + W_{ik}^+ C_{kj}\right) - \frac{f(tr(\boldsymbol{C}))C_{ij} - \delta_{ij}}{Wi_{\tau 0}}, \tag{5}$$

where $S_{ij}^+ = (\partial u_i^+/\partial x_j^+ + \partial u_j^+/\partial x_i^+)/2$ and $W_{ij}^+ = (\partial u_i^+/\partial x_j^+ - \partial u_j^+/\partial x_i^+)/2$ are, respectively, the terms of the rate-of-strain, $\boldsymbol{S}^+$, and the rate-of-rotation, $\boldsymbol{W}^+$, tensors. To stabilize the computations, a dissipative term is added in the FENE-P model equation [8,10,16,18,27,30–32,36]. A Schmidt number equal to 0.2 was found necessary to keep the algorithm stable and the conformation tensor symmetric positive-definite.

3. Numerical methodology

Since the numerical scheme for our direct numerical simulation (DNS) was already given in detail by Thais et al. [32], we present here a brief description of the mathematical and numerical approaches. The hybrid MPI/OPENMP algorithm used was tailored to run properly in massively parallel architectures. The hybrid spatial scheme includes Fourier spectral accuracy in the two homogeneous directions (x and y) and sixth-order compact finite differences for the first and second-order wall-normal derivatives (z direction). The time marching can be up to fourth-order accurate by the use of the Adams–Moulton scheme for the viscous terms and Adams–Bashforth for the explicit terms. Pressure–velocity coupling is facilitated by a higher order generalization of the semi-implicit fractional step method on a non-staggered grid arrangement analysed by [4]. In order to attenuate high wave-number energy accumulation, de-aliasing and fourth-order filtering are performed in the two homogeneous and wall-normal directions, respectively. Typically, this algorithm makes possible high-resolution, high drag reduction viscoelastic DNS, at relatively high flow Reynolds numbers.

In order to analyse the interaction of the polymer molecules with the turbulence from the very beginning to the steady state, the initial conditions for the conformation tensor were the identity tensor, $\boldsymbol{I}$ ($\boldsymbol{C} = \boldsymbol{I}$ at the beginning of the simulations). In addition, for each viscoelastic case, both the velocity and the pressure fields were initially started from the same Newtonian fully developed turbulent flow. As a result of this methodology, the DR exhibits a significant transient behaviour before achieving its statistical steady state, as we will show in the next section.