EFFECTS OF POLYMER ADDITIVES ON TURBOPHORESIS IN A TURBULENT CHANNEL FLOW

Gaetano Sardina[1,2], Arash Nowbahar[3], Francesco Picano [1] & Luca Brandt [1]
[1]*Linné FLOW Centre, SeRC (Swedish e-Science Research Centre), KTH Mechanics, SE-100 44 Stockholm, Sweden*
[2]*Facoltà di Ingegneria, Architettura e Scienze Motorie, UKE-Università Kore di Enna, 94100 Enna, Italy,*
[3]*Department of Chemical Engineering, The Grove School of Engineering, The City College of New York, CUNY, NY 10031, USA*

Abstract Turbophoresis is the migration of inertial particles towards the wall in a wall-bounded flow induced by turbulence. In this work, we analyze the effects of drag reducing polymer additives on turbophoresis in a turbulent channel flow. The numerical data set is obtained from a direct numerical simulation (DNS) of a turbulent channel flow of a viscoelastic fluid and laden with particles of different inertia. The results indicate that polymer additives decrease the turbophoretic drift. We establish that turbophoresis is reduced because of the smaller wall-normal variation of wall-normal fluid velocity fluctuations that occurs in all drag reducing flows. Hence a reduction of turbophoresis should be a common feature of all drag reducing flows such as fiber, bubble suspensions and MHD.

INTRODUCTION

The main phenomenology occurring in particle-laden wall flows is the so-called turbophoresis that consists in particle preferential segregation close to the wall up to hundred times the bulk particle concentration. Examples where turbophoresis may play a role include reactors, filters, aircraft engines and turbines. In such systems particle accumulation may negatively or positively affect the efficiency. Turbophoresis has been studied extensively in many configurations and with different approaches. In particular, the preferential particle flux towards the wall is linked to the particle bias in following sweep and ejection events, which characterize wall-turbulence. A strong correlation was found between accumulation and coherent near-wall structures that force the particles to remain in regions of slow moving fluid, i.e. low speed streaks, see [7, 5] . The particle inertia is described by the relaxation time τ_p that can be normalized with a characteristic time scale of the flow leading to the dimensionless parameter called Stokes number St. Small St represent particles that behave almost has fluid tracers, while large Stokes numbers correspond to particles that are unaffected by turbulent fluctuations. Turbophoresis peaks when τ_p is of the order of the characteristic time of near-wall coherent structures (buffer layer), corresponding to about 20 viscous time scales ($St^+ = 20$). While inertial particles has been studied only in Newtonian fluids, polymer solutions are of definitive interest due to commercial and industrial relevance e.g. paints with proper metal powder. The addition of polymers to Newtonian fluids presents interesting properties, among them the most important is the drag reduction [8]. Though a precise description of the drag reduction mechanism is still lacking, it is known that polymer additives deeply change the coherent structures of the near-wall regions leading to the an increase of the streamwise velocity fluctuation and a reduction of the cross-stream components [2]. We will show that the alteration of the wall turbulence deeply affects the particle dynamics. A recent paper [3] investigate at the effects of polymer additives on small-scale clustering of heavy and light inertial particles in homogeneous isotropic turbulence. They find that depending on particle and flow parameters, Stokes number and Weissenberg number (ratio between polymer relaxation time τ_{pol} and a characteristic time scale of the flow), polymers can either increase or decrease clustering. The aim of the present work is to study for the first time the effects of polymer additives on turbophoresis. It is known that turbophoresis and small-scale clustering are deeply linked, see [6]. In contrast to the case of small-scale clustering, results show the wall particle concentration is always lowered by the presence of polymer additives, i.e. turbophoresis is reduced.

METHODOLOGY AND RESULTS

Turbophoresis is addressed by analyzing data of a DNS of a particle-laden turbulent channel flow at a friction Reynolds number $Re_\tau = u_\tau h/\nu = 150$. The pseudo-spectral Eulerian flow solver uses the FENE-P model to account the effects of the polymer solution, while a Lagrangian solver is used to track the position and velocity of particle population with different Stokes number. For the dispersed phase we assume a dilute suspension of particles made of rigid spheres whose diameters are smaller than the viscous scales of turbulence and density much larger than that of the fluid. The only force acting on these particles is the viscous Stokes drag, hence we neglect particle feedback on the carrier phase, inter-particle collisions and mutually hydrodynamic coupling [4]. The Lagrangian evolution of the particles is given by:

$$\frac{d\mathbf{v_p}}{dt} = \frac{\mathbf{u}(\mathbf{x_p}, t) - \mathbf{v_p}}{St}(1 + 0.15Re_p^{0.687})\,\chi(Wi_p), \qquad \frac{d\mathbf{x_p}}{dt} = \mathbf{v_p}; \tag{1}$$

where x_p and v_p are the position and velocity of the $\mathrm{p^{th}}$ particle, $Re_p = |\mathbf{v_p} - \mathbf{u_p}|d_p/\nu$ is the particle Reynolds number (d_p particle diameter, ν kinematic viscosity). The correction factor $\chi(Wi_p)$ is introduced in the Stokes drag to account for

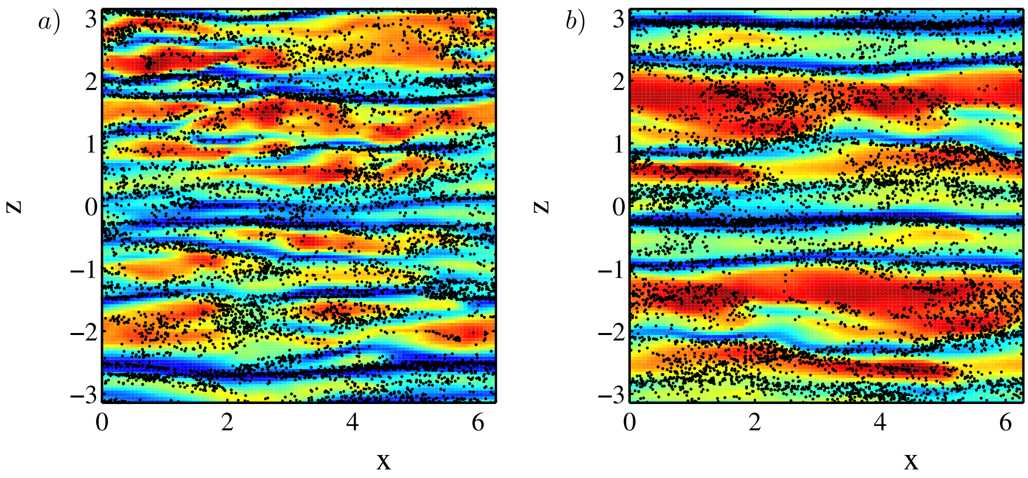

Figure 1. Snapshot of an $x - z$ plane in the buffer layer for $a)$ Newtonian case and $b)$ polymeric flow. Black dots represent particles at $St^+ = 20$, and colors indicate the magnitude of the stream-wise velocity component, red being highest and blue lowest.

the effects of a finite Weissemberg number at the particle size, $Wi_p = \tau_{pol}\, |v_p - u|/(d_p/2)$. The values of the correction factor χ have been extrapolated by fitting the experimental data described in [1]. Four particle populations are considered $St^+ = 0, 1, 10, 20$ with a total of 1,000,000 particles per simulation.

Figure 1 shows an instantaneous snapshot of a wall-parallel plane in the buffer region $5 < y^+ < 30$. The contours represent the streamwise fluctuation u'_x of the carrier fluid velocity, red being highest and blue the low-speed fluid. Black dots represent the particles around that plane and the snapshot is taken at statistical steady state. For the Newtonian case, we see streaks of low and high speed fluid, as well as streaks of particles aligning preferentially in the regions of low-speed fluid. This phenomenon is well documented in several works, e.g. [7], and is a characteristic of fully developed statistically steady states, [5]. In these conditions, when the mean particle concentration profile does not change any more, the turbophoretic drift is balanced by the oversampling of the fluid motions departing from the wall, those associated to the low-speed streaks. Hence, particles are found to preferentially accumulate in elongated structures localized in the low fluid-velocity streaks at statistical steady state.

Figure 1$b)$ shows a similar snapshot for the viscoelastic flow. It is confirmed that polymers tend to widen the streaks occurring in the velocity field [2]. The effects of polymers on the flow are mostly seen in the buffer layer, where they increase the fluids resistance to extensional deformation, making eddies wider and less frequent. In this flow, inertial particles, like in Newtonian flow, align into streaks; however we see a decreased tendency to preferentially localize in low-speed regions. With the widening of these streaks, the particles appear to experience less clustering: they are spread out more than in the Newtonian case. The ability of the particle to sample different wall-structures in the Newtonian and polymeric case, described qualitatively in the plots, will reflect in a reduction of the turbophoretic drift and particle segregation at the wall. A quantitative analysis of the reduction of the wall particle concentration by means of polymers together with a simple model that links the turbophoretic drift with the wall-normal derivative of the wall-normal Reynolds stress will be presented at the conference.

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