Wall drag modification by large deformable droplets in turbulent channel flow

CrossMark

Luca Scarbolo *, Alfredo Soldati

[a] *Department of Elec. Manag. and Mechanical Engineering, University of Udine, 33100 Udine, Italy*
[b] *Department of Fluid Mechanics, CISM, 33100 Udine, Italy*

ABSTRACT

The role of deformability in the wall-drag modification produced by the dispersion of large deformable droplets in turbulence is investigated by Direct Numerical Simulations (DNS) of a turbulent channel flow ($Re_\tau = 150$) coupled with the Phase Field Model (PFM) description of the droplets. The two fluids have the same density and viscosity, and a wide range of interface deformability is considered by changing the Weber number: $We = 0.18$–2.8. The results show wall-drag modifications that depend on the droplets deformability: when the deformability is low (small We), a significant Drag Enhancement (DE) is observed; increasing the deformability the DE is reduced and negligible effects are observed when the Weber number is sufficiently large. The DE is likely due to droplets velocity that reduces increasing the deformability, introducing an obstruction to the flow and increasing drag.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Swarms of large deformable bubbles dispersed in wall bounded turbulence produce significant modifications of the wall drag; these effects have been investigated by many authors, focusing on the quantification of drag and evidencing situations where large amount of Drag Reduction (DR) can be observed [1–3]. In spite of its practical relevance, the mechanism underpinning the wall-drag modification in presence of large deformable bubbles is still not clear and only few recent studies proposed a detailed analyses of the droplet–turbulence interactions [4,5]. The Direct Numerical Simulations (DNS) of Lu et al. [4] highlighted the role of bubbles deformability in the wall-drag modification produced by a large number of bubbles with the same viscosity of the surrounding fluid and with a small density ratio ($\rho_f/\rho_d = 10$). They observed that deformable bubbles released in a turbulent channel flow could produce Drag Reduction (DR) or Drag Enhancement (DE), according to their deformability. Two mechanisms were proposed: (i) bubbles characterized by large deformability produced a near-wall streamwise vorticity canceling, resulting in DR; (ii) bubbles with small deformability were slowed down by the near-wall flow field, producing an obstruction to the flow and resulting to DE. The recent experimental work of van Gils et al. [5] showed important

DR (up to 40%) when large deformable bubbles (with viscosity ratio $\rho_f v_f/\rho_b v_b = 100$ and a density ratio $\rho_f/\rho_d = 1000$) were released in a turbulent Taylor–Couette flow, emphasizing the central role of the bubbles deformability. In order to further clarify the role of the deformability in the contest of large deformable bodies dispersed in turbulent wall-bounded flows, in this work the problem has been simplified neglecting the density and the viscosity differences between the two fluids, retaining the surface tension σ only. The physical system defined through these simplifications is governed by two leading effects: (i) droplet deformability, that is controlled by the surface tension; (ii) droplet inertia that is comparable to that of the surrounding fluid. As a result the problem is set to its simplest configuration, highlighting the surface tension effects and allowing a parametric analysis of the droplet deformability that can be varied between two limit cases: the single phase flow ($\sigma = 0$, $We \to \infty$) and the dispersion of rigid fluid spheres ($\sigma \to \infty$, $We = 0$). To the best of our knowledge this work represents one of the first attempts to analyze and model the interaction between turbulence and deformable droplets, considering only the surface tension effects.

2. Governing equations

In this work the wall-drag modification produced by a large number of deformable droplets dispersed in wall-bounded turbulence has been studied. The flow field evolution has been described with DNSs of a modified incompressible Navier–Stokes equations

* Corresponding author. Tel.: +39 0432855005.
  E-mail addresses: luca.scarbolo@uniud.it (L. Scarbolo), soldati@uniud.it (A. Soldati).

coupled with the Phase Field Model (PFM) description of the fluid–fluid interfaces.

2.1. The phase field model

In the PFM, the interface between two fluids is considered as a layer of finite thickness rather than a sharp discontinuity. Across the interfacial layer the physical properties of the fluid components vary in a smooth and continuous way from one fluid to the other. The state of the system is described, at any time, by a scalar order parameter ϕ, which is a function of the position vector $\mathbf{x}$. The order parameter directly represents one of the physical properties of the fluid, such as its density, its molar concentration, etc.; all the remaining properties are in turn modeled as proportional to the scalar order parameter $\phi(\mathbf{x})$ [6,7]. Due to the continuous description of the interface, also the order parameter is continuous over the entire domain and it shows smooth variations across the interface between single fluid regions, where it assumes mostly uniform values. Coupling the continuous representation of the two fluid field with a transport equation of the order parameter, the system evolution can be resolved in time. One of the best-known PFM is the Cahn–Hilliard equation [8,9], where the evolution of the order parameter is driven by the minimization of a thermodynamical conservative chemical potential. As a result the conservation of the phase field is ensured and the diffusion of the interfacial layer is overcame, granting more accuracy in the computation of the interfacial forces [7] and avoiding the major drawback of the most common interface-tracking methods [10]. The convective Cahn–Hilliard equation is written as follows:

$$\frac{\partial \phi}{\partial t} = -\mathbf{u} \cdot \nabla \phi + M \nabla^2 \mu, \tag{1}$$

where $\mathbf{u}$ is the velocity field, M is the mobility parameter that controls the interface relaxation time and μ is a chemical potential that controls the interfacial layer behavior. Eq. (1) models the evolution in time of a diffuse interface, in particular it can describe the conservative advection of a diffuse interface [11,12] and complex changes in the interface topology. The chemical potential μ is defined in terms of the free energy functional $f[\phi]$ as follows:

$$\mu = \frac{\delta f[\phi(\mathbf{x})]}{\delta \phi}, \tag{2}$$

where $f[\phi]$ is a conservative, thermodynamically consistent functional that can assume suitable definitions according to the problem under analysis and it. The PFM representation of an immiscible binary mixture of isothermal fluids is given by the following free energy functional:

$$f[\phi(\mathbf{x})] = f_{id} + \frac{1}{2} \kappa |\nabla \phi|^2$$
$$= \frac{\alpha}{4}\left(\phi - \sqrt{\frac{\beta}{\alpha}}\right)^2 \left(\phi + \sqrt{\frac{\beta}{\alpha}}\right)^2 + \frac{1}{2}\kappa|\nabla\phi|^2. \tag{3}$$

In this work, the scalar order parameter ϕ represents the relative concentration of the two fluid components. The first term on the right-hand-side of Eq. (3), f_{id}, is the ideal part of the free energy that accounts for the tendency of the system to separate into pure fluid clusters. For two immiscible fluids, the phobic behavior is described by a double-well formulation which shows two minima corresponding to the two stable fluid phases that are defined through the positive constants α and β. The two fluids are allowed to mix into the interfacial layer where they store a mixing energy which is accounted by the non-local term $1/2\kappa|\nabla\phi|^2$ of Eq. (3) and which is the source of the surface tension in the PFM. The relative concentration equilibrium profile across the interface is given by

the competition of the two terms appearing in the free energy formulation and can be obtained by minimizing the free energy functional with respect to the variations of the order parameter:

$$\mu = \frac{\delta f[\phi]}{\delta \phi} = 0 \Rightarrow \alpha \phi^3 - \beta \phi - \kappa \nabla^2 \phi = 0. \tag{4}$$

Integration of Eq. (4) for a one-dimensional planar interface, where $\phi(z \to \pm\infty) = \phi_\pm$, yields two stable solutions $\phi_\pm = \pm\sqrt{\beta/\alpha}$ and the following non-uniform solution:

$$\phi(z) = \phi_+ \tanh\left(\frac{z}{\sqrt{2}\xi}\right). \tag{5}$$

The capillary width $\xi = \sqrt{\kappa/\beta}$ is the interface length scale; $0.9\phi_- \leqslant \phi \leqslant 0.9\phi_+$ in a layer of 4.164ξ that contains the 98.5% of the interface surface tension [6,12]. At the equilibrium, the surface tension σ is:

$$\sigma = \kappa \int_{-\infty}^{+\infty} \left(\frac{\mathrm{d}\phi}{\mathrm{d}z}\right)^2 \mathrm{d}z = \frac{\sqrt{8}}{3}\frac{\kappa^{\frac{1}{2}}\beta^{\frac{3}{2}}}{\alpha}. \tag{6}$$

Once the interface thickness ξ and the equilibrium solutions $\phi_\pm$ are chosen, Eq. (6) allows to define the free energy parameters α, β and κ necessary to achieve the desired surface tension value. The derivation described above has been adopted and reviewed by several authors [13,14] and the convergence of Eq. (1) to the "sharp interface limit" has been recently proven [15]. In particular, although the fictitious widening of the interface necessary for its numerical resolution,[1] the PFM can describe the desired value of σ by defining the free energy functional coefficients and adopting a proper scaling between the capillary width ξ and the interface mobility M [12,15].

2.2. Coupling with the flow field

The evolution of the velocity field $\mathbf{u}$ is described by the incompressible Navier–Stokes equations provided by a phase field-dependent surface force [16]:

$$\nabla \cdot \mathbf{u} = 0, \tag{7}$$

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \cdot \nabla \mathbf{u} - \nabla p + \nu \nabla^2 \mathbf{u} + \mu \nabla \phi, \tag{8}$$

where p is the pressure term and ν is the kinematic viscosity. The coupled Chan–Hilliard/Navier–Stokes (CHNS) Eqs. 1, 7 and 8 is the so-called "Model-H" [17], where the surface tension forcing $\mu\nabla\phi$ is derived from the Korteweg stress.

3. Numerical simulations

3.1. Geometry and numerical scheme

In this work a swarm of droplets of initial diameter d dispersed in a fully developed turbulent channel flow is simulated; the two fluids are considered immiscible, incompressible, Newtonian, density-matched and viscosity-matched. With this assumptions the system is set to its simplest configuration, allowing to isolate the surface tension effects and the role of droplets deformability on the wall-drag modification. With reference to Fig. 1 the coordinate system is located at the center of the channel and x-, y- and z-axes point in the streamwise, spanwise and wall-normal directions, respectively. The size of the channel is $4\pi h \times 2\pi h \times 2h$ in x, y, and z directions, respectively, and h is the channel half-height. The droplets are initialized by superposing the phase field ϕ over

---

[1] At least three mesh-points are necessary to fully resolve the interface with the current methodology employed. Larger number of mesh-points can be required according to the accuracy of the numerical scheme adopted.