Delft University of Technology

DNS of turbulent channel flows laden with finite-size particles at high volume fractions
Extended abstract

Francesco, Picano; Breugem, Wim-Paul; Luca, Brandt

Publication date
2013

Document Version
Final published version

Published in
Proceedings of 14th European Turbulence Conference

Citation (APA)
Francesco, P., Breugem, W.-P., & Luca, B. (2013). DNS of turbulent channel flows laden with finite-size particles at high volume fractions: Extended abstract. In *Proceedings of 14th European Turbulence Conference* Zakon Group.

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

DNS OF TURBULENT CHANNEL FLOWS LADEN WITH FINITE-SIZE PARTICLES AT HIGH VOLUME FRACTIONS

Picano Francesco[1], Breugem Wim-Paul [2] & Brandt Luca [1]
[1]*Linné FLOW Centre, KTH Mechanics, Stockholm, Sweden*
[2]*Laboratory for Aero & Hydrodynamics, TU-Delft, Delft, The Netherlands*

Abstract Suspensions are often found in different processes and applications, e.g. sediment transport in environments or pharmaceutical engineering. The laminar regime in the semi-dilute or dense cases, non vanishing volume fraction, is usually characterized by the sometime spectacular rheological properties induced by the suspended phase. Much less is known about dissipation and mixing in the turbulent regime. The aim of the present work is to investigate the turbulent channel flow of a fluid laden with rigid spherical particles at a fixed bulk Reynolds number $Re_h = U_0 h/\nu = 2800$. The particle radius is selected to be 18 times smaller than the channel half-width. Fully-resolved Direct Numerical Simulations with particle tracking and Immersed Boundary Method are presented for values of the volume fraction up to $\phi = 0.2$. As expected for "large" particles, the overall drag increases with the volume fraction. We show that the presence of the particles deeply changes flow behavior, as already evident from the mean velocity profile with the canonical regions, buffer- or log-layer, strongly altered.

INTRODUCTION

Fluids with a suspended solid phase frequently occur in environmental processes and in industrial applications. Sometimes laminar flow conditions take place as in magmatic flows, but often turbulent regimes appear as in the sediment transport in rivers. In industrial processes, the flow is usually turbulent in order to achieve high flow rates. When the suspended phase is not that dilute, its effect on the fluid property is not negligible. In this context, many studies dealt with the rheological properties of laminar suspensions from the dilute to the dense case, see e.g. [2]. It is well known that the presence of particles induces an increase of the effective viscosity of the suspension [5] and may generate normal stress differences at large volume fractions. It has been observed that, at high shear rates and fixed volume fraction, the viscosity may increase with the shear rate, i.e. the so-called shear-thickening [5].

Turbulent and transitional flows are usually characterized by a shear rate that intermittently fluctuates in space and time. This feature, in combination with the peculiar rheological features of semi-dilute/dense suspensions, lead to new phenomenologies in these chaotic flow regimes. As an example, the experiments in [3] show that in pipe for and for relatively large particles, the critical Reynolds number at which transition to turbulence occurs cannot be simply rescaled considering the increase of the effective viscosity due to the presence of the solid phase. Recently, a DNS study of turbulent channel flow laden with finite-size particles has been presented in [4] investigating volume fractions up to $\phi = 0.07$. The authors show that particles interact with the near wall turbulent structures inducing an increase the turbulent drag especially at the highest volume fraction they considered, i.e. $\phi = 0.07$. The aim of the present work is to understand how the presence of a solid particulate phase at high volume fraction, $\phi = 0.2$, alters the turbulence in channel flows. The turbulent drag appears to increase with the volume fraction, but we do not find a simple rescaling in terms of effective viscosity. A deep change in the structure of the classic near-wall turbulence occurs that already strongly alters the mean velocity profile.

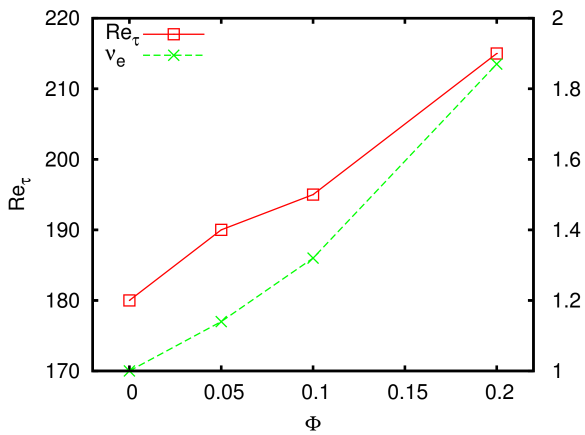
METHODOLOGY

Direct numerical simulations have been performed by using an algorithm that fully describes the coupling between the solid and fluid phases. The incompressible Navier-Stokes equations are discretized by second order finite differences on a staggered mesh. The finite-size particles are evolved by a Lagrangian algorithm that solves the linear and angular momentum equations. The coupling between the two phases is directly achieved by using an Immersed Boundary Method. Lubrication models are also used to correctly reproduce the interaction between particles when their gap distance is smaller than the mesh size. The code was fully validated against several test cases, see [1] for more details.

Simulations of turbulent channel flow were performed in a domain of length $6h$, $2h$ and $3h$ in the streamwise, wall-normal and spanwise directions, respectively. Periodic boundary conditions are enforced in the streamwise and spanwise directions, while no slip is prescribed at the wall. The bulk velocity $U_0 = \int_A U dA$ is kept constant by adjusting the mean pressure gradient so that the bulk Reynolds number $Re_h = U_0 h/\nu = 2800$ (ν the fluid kinematic viscosity). The domain is discretized by a cubic mesh with $864 \times 288 \times 432$ points in the streamwise, wall-normal and spanwise directions. Non-Brownian spherical particles with same density as the fluid are considered with the ratio between the particle radius and the channel half-width fixed at $a/h = 1/18$. Three different volume fractions, $\phi = 0.05; 0.1; 0.2$, have been examined in addition to the single phase case for a direct comparison. It should be noted that the present DNSs of turbulent channel flow laden with finite-size particles are the largest simulations in terms of domain size and volume fraction considered.

RESULTS & DISCUSSION

The presence of particles in semi-dilute/dense regimes alters the turbulent features of the channel flow. At constant mass flux, the friction velocity $u_* = \sqrt{(dP/dx)h/\rho}$ or equivalently the friction Reynolds number $Re_\tau = u_* h/\nu$ measures the overall drag needed to flow the suspension. At the present flow rate, the friction Reynolds number of the unladen case is $Re_\tau = 180$, while it increases up to $Re_\tau \simeq 215$ at the maximum volume fraction here considered, $\phi = 0.2$, as shown in the left plot of figure 1. No simple rescaling has been found considering the increase of the effective viscosity of rigid sphere suspensions, e.g. Eiler fit $\nu_e = \nu\,(1 + 1.25\,\phi/(1 - \phi/0.63))$ [5]. It should be noted that the particles are large compared to the smallest scales of turbulence being their radius of the order of 10 viscous lengths ν/u_*. As mentioned above it is interesting that also in transitional flows with "large" particles no simple rescaling laws have been found for the critical Reynolds number [3]. The back-reaction of the particles on the turbulent flow deeply alter its structure. The mean velocity profiles $U^+ = U/u_*$ vs the wall normal distance $y^+ = y/(\nu/u_*)$ are shown in the right panel of figure 1. For volume fractions $\phi \leq 0.05$, the particles increase the turbulent drag, as evidenced by the smaller values of U^+ in the outer part of the rescaled velocity, but do not significantly alter the shape of the mean profile. Increasing the volume fraction, the mean velocity profile deeply changes. In particular, the buffer layer disappears and the log-layer region, though still present, show very different slopes. The interaction between a fluctuating shear rate field and the particle dynamics in dense regime may lead to these strong modifications. A complete analysis of the velocity and particle statistics and of the mutual interactions between fluid and solid phases will be presented at the conference.



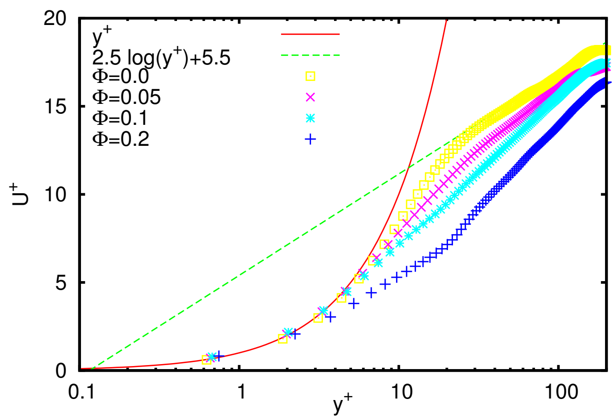


Figure 1. Left panel: friction Reynolds number Re_τ and laminar effective viscosity (Eilers fit) $\nu_e = \nu\,(1 + 1.25\,\phi/(1 - \phi/0.63))$ vs volume fraction ϕ. Right panel: Mean velocity profile normalized by the friction velocity $U^+ = U/u_*$ vs wall normal distance rescaled in viscous units $y^+ = y/(\nu/u_*)$ for different volume fractions.

References

[1] Wim-Paul Breugem. A second-order accurate immersed boundary method for fully resolved simulations of particle-laden flows. *J. Comp. Phys.*, **231**(13):4469 – 4498, 2012.

[2] É. Guazzelli and J.F Morris. *A Physical Introduction to Suspension Dynamics*. Cambridge Univ Press, 2011.

[3] J.-P. Matas, J. F. Morris, and É. Guazzelli. Transition to turbulence in particulate pipe flow. *Phys. Rev. Lett.*, **90**:014501, Jan 2003.

[4] Xueming Shao, Tenghu Wu, and Zhaosheng Yu. Fully resolved numerical simulation of particle-laden turbulent flow in a horizontal channel at a low reynolds number. *Journal of Fluid Mechanics*, **693**:319–344.

[5] J.J. Stickel and R.L. Powell. Fluid mechanics and rheology of dense suspensions. *Annu. Rev. Fluid Mech.*, **37**:129–149, 2005.