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Lattice-Boltzmann simulations of particle transport in a turbulent channel flow

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ABSTRACT

The lattice-Boltzmann Method (LBM) is employed to directly simulate the transport of particles approximated as 'point particles' in a turbulent channel flow. Prior experimental studies have shown that particles preferentially move toward the wall or center in a pipe flow depending on their Stokes number (*St*). The simulations are carried out for a range of *St* and they reproduce the observed experimental behavior. Since the only effect that can influence the transport in the cross-flow direction is turbulence in the context of the simulation framework adopted here, it is concluded that turbophoresis is responsible for the behavior.

1. Introduction

Particle-laden flows are important owing to their relevance to many engineering applications such as pollution control, transport systems, and fluidized beds [1–3]. For example, in fluidized beds, which are widely employed in gasification and combustion applications, the design and optimization involve controlling the spatial distribution of particles. In the pharmaceutical industry, the transport of particulate media in pipes is encountered in several processes. An effective delivery system has to be designed to distribute the particles uniformly in space and avoid particle deposition on the wall. Another example is the removal of pollutant particles from gases, wherein a cyclone separator is employed causing the particle to migrate and deposit on the wall. The range of applications reflects the importance of understanding the fundamental interactions between the particles and flow in dispersed media.

In particle-laden flows, an important non-dimensional parameter that characterizes particle-transport is the Stokes number, *St*. The *St* is defined as the ratio of particle response time to the flow time scale, i.e.

$$St = \frac{\tau_p}{\tau_f}. \tag{1}$$

The particle time constant is generally used as a measure of the response time of the particle. If the particle density is much higher than the fluid density, the particle time constant, τ_p is given as, [4]

$$\tau_p = \frac{\rho_p d_p^2}{18\mu}. \tag{2}$$

The flow response time can be obtained as

$$\tau_f = \frac{L}{U}, \tag{3}$$

where L and U represent a characteristic length and velocity scale, respectively. For instance, in the case of a channel flow, L can be taken as the channel height and U as the maximum mean velocity. For turbulent flow in a channel of height, H, St can be written as,

$$St = \frac{\rho_p d_p^2 U}{18\mu H}. \tag{4}$$

Confined particle-laden flows have been studied by several researchers in the past. Segre and Silberberg [5,6] studied the lateral migration of neutrally buoyant particles in a laminar pipe flow. They found that particles move to an equilibrium position in the pipe that is mid-way between the wall and the axis of the pipe. This effect is referred to as Segre-Silberberg effect. Feng et al. [7,8] did numerical simulations of two-dimensional cylindrical particles in a laminar channel flow. They were able to recover the Segre-Silberberg effect. They identified that this effect is caused by the balance of three forces acting on the particle: Saffman lift

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[9], Magnus lift [10] and wall repulsion [11,12]. Mortazavi and Tryggvason [13] performed numerical simulations of drops in a laminar channel flow. They observed that at high *Re*, the drops began to oscillate about the center of the channel.

Nourbakhsh et al. [14] performed simulations of drops in a Poiseuille flow and have studied the effect of drop deformation on the drop movement. They found that drops with small deformation migrate to an equilibrium position half-way between the wall and the center (Segre-Silberberg effect [5,6]), while highly deformable drops migrate to the center of the channel.

Jebakumar et al. [15] studied the Stokes number (*St*) dependence of particle movement in a laminar channel flow through resolved computations by employing the lattice-Boltzmann method (LBM). They found that the Saffman lift, Magnus lift and wall repulsion affected the particle migration. They reproduced the Segre-Silberberg effect and showed that at low *St*, particles settled at an equilibrium position near the wall, while at high *St*, particles tend to oscillate about the channel centerline. Zhang et al. [16] studied the regime of transition *St* where particles move from near the wall and start oscillating about the center. They found that oscillations arise when the Saffman lift and inertial forces are comparable.

The studies reported so far are for laminar flows. Lau and Nathan [17] have studied the transport of particles in a turbulent pipe flow. They noticed that the radial particle concentration at the exit of the pipe was not uniform. The particles migrated toward or away from the axis depending on their *St*. Fig. 1 shows the concentration profile of particles, Θ, normalized by the bulk concentration, Θ_b at the exit of a turbulent pipe flow. At a low *St* of 0.3, the particle concentration near the wall is about 2.5 times the bulk concentration. For a *St* of 11.2, the particle concentration is high near the axis of the pipe. Particles with a *St* of 1.4 are distributed almost uniformly. Thus, as the *St* increases from 0.3 to 11.2, the radial concentration profile changes from a 'U-shape' to a '$\wedge$-shape'. The reason for this preferential migration is not well understood.

Shao et al. [18] numerically studied the effect of particles on turbulent intensities in a channel flow. They found that particle sedimentation on the walls can increase turbulent intensity from vortex shedding. If sedimentation effect is negligible, particles decrease streamwise fluctuations of large scale vortices. Kidanemariam et al. [19] carried out simulations of particles in open channel flow. They found that particles lag the fluid velocity and tend to reside in low-speed streaks.

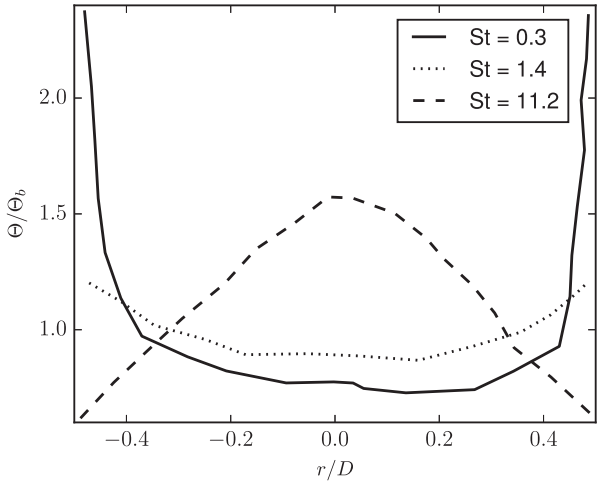

Fig. 1. Concentration profile of particles at the exit of a turbulent pipe flow (adapted from Lau and Nathan [17]).

Li et al. [20] numerically studied the effect of particle motion on the carrier phase. They found that particle feedback causes the turbulence to become more anisotropic as mass loading is increased. Kulick et al. [21] experimentally investigated turbulence modulation by particles in a channel flow. They found that turbulence was attenuated by the addition of particles. The degree of attenuation increased with Stokes number, mass loading and distance from the wall. Attenuation is stronger in the transverse direction than in the streamwise direction.

While there are several studies focusing on turbulence modulation by particles, to the authors' best knowledge that there are no numerical studies of particle transport in wall-bounded flows that clarify the mechanism responsible for the transport toward the wall or away from it. In this study, the lattice-Boltzmann method (LBM) is employed to carry out direct numerical simulations of particles approximated as point-particles in the limit of d_p less than the Kolmogorov length scale, η_k. The next section discusses the computational method. This is followed by presentation of the results and their discussion from the point-particle direct numerical simulations (PP-DNS). The paper ends with summary and conclusions.

2. The computational method

The lattice-Boltzmann method (LBM) is employed for our computations. The LBM is a kinetic solver derived from the Boltzmann equation by discretizing the velocity space with finite velocities. The Boltzmann equation is

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \boldsymbol{c}\cdot\nabla_{\boldsymbol{x}} f + \boldsymbol{F}\cdot\nabla_{\boldsymbol{c}} f = C_{12}, \tag{5}$$

where f is the single molecule velocity distribution function, t is time, $\boldsymbol{c}$ is the molecule speed, $\nabla_{\boldsymbol{x}}$ and $\nabla_{\boldsymbol{c}}$ represent the gradient in physical and velocity space and $\boldsymbol{F}$ represents external forces. C_{12} represents the effect of two molecule collisions. The LBM has its origins in the lattice-gas automaton (LGA) method in which the solution procedure involves the movement of "particles" on discrete lattices with discrete velocities to mimic fluid motion [22,23]. To avoid confusion between the physical particles being simulated in this study and the "particles" often referenced in LGA and LBM, the latter will be referred to as "molecules". The "molecules" are constrained to move only in certain directions. A three-dimensional D3Q19 lattice for the discrete velocities is employed in this work. Fig. 2 shows a D3Q19 lattice. Chen et al. [24] have shown by performing a Taylor-series expansion in time and space and by using the Chapman-Enskog expansion that the Navier-Stokes equations can be recovered from the LB equations. In this work, the multiple relaxation time (MRT) collision operator [25–27] is used to represent the effect of collisions. The MRT collision operator has been used because it has been shown to have superior numerical stability and is thus suited to simulate high Reynolds number (*Re*) flows [25]. With the MRT collision operator and the forcing term, the generalized lattice-Boltzmann equation (GLBE) can be written as [28]

$$f_\alpha(\boldsymbol{x}+\boldsymbol{e}_\alpha\delta_t, t+\delta_t) - f_\alpha(\boldsymbol{x},t) = -\sum_\beta \Lambda_{\alpha\beta}(f_\beta - f_\beta^{eq}) + \sum_\beta \left(I_{\alpha\beta} - \frac{1}{2}\Lambda_{\alpha\beta}\right) S_\beta \delta_t, \tag{6}$$

where f_α is the discrete single molecule velocity distribution function in the direction α, $\boldsymbol{x}$ is the co-ordinates of the lattice point, $\boldsymbol{e}_\alpha$ is the discrete velocity in the direction α, $\Lambda_{\alpha\beta}$ is the relaxation matrix, $I_{\alpha\beta}$ is the identity matrix, f_β^{eq} is the discrete form of the equilibrium distribution function in the direction β and S_β is the source