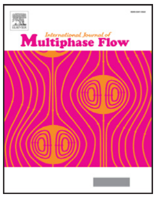
International Journal of Multiphase Flow 98 (2018) 45–55

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



Particle segregation in turbulent Couette–Poiseuille flow with vanishing wall shear

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ARTICLE INFO

Article history:
Received 19 June 2017
Revised 16 August 2017
Accepted 1 September 2017
Available online 5 September 2017

Keywords:
Particle-laden flow
Turbulent Couette–Poiseuille flow
Inertial particle distribution
Large-scale structures

ABSTRACT

Inertial particles dispersed in wall-bounded flows in pipes and channels are known to accumulate close to the walls. The segregation ability depends greatly on the inertia-selection effects of the near-wall quasi-coherent turbulent structures, which are formed near both walls where shear stresses are high. Here, however, we investigated if and how particles segregate in the vicinity of walls in absence of mean shear. A tailor-made turbulent Couette–Poiseuille flow was designed such that the mean shear vanished at the moving wall, thereby resulting in an asymmetric flow with conventional near-wall turbulent structures only at one wall. In addition, Large-Scale Structures (LSSs) were observed in the flow, which greatly influenced the distribution of the inertial particles. Particles of five different inertia groups were embedded in the directly simulated turbulence field and examined. It was found that particles of high inertia segregated near the stationary wall where mean shear prevailed, but also near the moving wall where mean shear was absent. However, due to the qualitatively distinct near-wall flow structures, the inertia effects on the actual segregation were different at the two walls. Mechanisms causing the asymmetric wall-normal segregation were explored with the focus on the moving-wall region, where the quasi-coherent turbulent structures were absent, and the local fluid structures were dominated by imprints of the LSSs.

1. Introduction

Particle-laden turbulent flows are prevalent in many industrial applications and environmental processes. Examples include dispersion of carbonaceous dust or chemicals, the huge amount of plankton species in the ocean, transport of pollutants in the air, and natural processes such as formation of clouds and rain in the atmosphere and sediment transport in rivers. The dynamics of inertial particles in turbulence and their interactions with the containing fluid have received continuous consideration in various flow configurations in the past decades. However, the commonly encountered flow scenarios are still far from being fully covered and particle mixing in inhomogeneous and anisotropic turbulence remains a largely open question.

Among various scenarios, dispersion of small inertial particles in a pressure-driven turbulent plane channel flow (also known as a turbulent Poiseuille flow) is widely documented. The governing equation for the motion of spherical solid particles in non-uniform flows was first proposed by Maxey and Riley (1983) under the condition that the Reynolds number based on the radius of the sphere is smaller than unity. Based on this theoretical model, McLaughlin (1989) was the first to use Direct Numerical Simulation (DNS) coupled with Lagrangian particle tracking to study aerosol particle deposition in a turbulent Poiseuille flow (referred to as P flow henceforth) at low Reynolds number.

It has been extensively reported that initially randomly-distributed particles in a turbulent P flow will accumulate in the near-wall region, in particular in the viscous sublayer, under the effects of inertia. This phenomena is often referred to as “turbophoresis”, a term literally meaning particle transport operated by turbulence, which was firstly proposed by Caporaloni et al. (1975) and later developed and refined by Reeks (1983, 2005, 2014). There have been several influencing factors that lead to a final segregation. Brooke et al. (1994) separated the particle flux into three groups according to their origin, namely the free-flight flux, the turbophoretic flux and the diffusive flux. They found that the near-wall accumulation resulted mainly from free-flights that do not enable particles to bounce back from the wall, while aided by turbophoresis.

Particle segregation is determined by the coupling between particle inertia and the surrounding fluid structures. Particle inertia is often measured by a non-dimensional parameter, namely the Stokes number (St), defined as the ratio of the particle re-

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http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.09.001

sponse time (τ_p) to the timescale of the underlying fluid flow (τ_f). The Stokes number reflects the time the particles need to adjust their motions following the variation of the local fluid. The Stokes number for a P flow is often defined using wall units, i.e. $St = \tau_p/\tau_f$ where $\tau_f = \nu/u_\tau{}^2$ and ν is the kinematic viscosity of the fluid and u_τ is the friction velocity at the wall. Previous studies have demonstrated that the strongest near-wall segregation follows a non-monotonic trend with *St*. For example, for a P flow with $Re_\tau = 180$ (Re_τ based on the friction velocity u_τ and the channel half-height *h*), the strongest near-wall segregation is found at $St \approx 20 \sim 30$, while either decreasing or increasing *St* will lead to a weaker segregation (Marchioli and Soldati, 2002; Picciotto et al., 2005; Soldati and Marchioli, 2009). The *St*-dependency of near-wall deposition is evaluated by Narayanan et al. (2003), who proposed three different regimes: the Brownian diffusion (for $St < 0.2$), the diffusion-impaction regime ($0.2 < St < 20$) and the inertia-moderated regime ($St > 20$).

The carrying flow undertakes inertia-selection of the particles. The quasi-coherent streaky structures and the associated elongated streamwise vortices are the most prominent structural features of wall-bounded flows in the inner layer ($z^+ < 60$) (Jeong et al., 1997; Schoppa and Hussain, 2002). When particles are added into the turbulence, the combined effects of the near-wall quasi-coherent turbulent structures together with particle inertia determine the final segregation in the viscous sublayer (Kaftori et al., 1995a,b; Rouson and Eaton, 2001; Marchioli and Soldati, 2002, 2009). In particular, Marchioli and Soldati (2002) provided a detailed description of the mechanism for the optimal *St* for maximum near-wall segregation. They pointed out the important inertia-selection effects of the offspring streamwise vortices inhabiting the particles to leave the wall. The ability to successfully escape the wall region depends on the particle inertia, or *St*. Tracer-like particles follow the flow perfectly and obey the fluid continuity, whereas particles of large-inertia (e.g. $St = 100$) with strong wall-ward momentum hit the wall and bounce back into the outer flow while ignoring the offspring streamwise vortices. Particles with intermediate inertia (e.g. $St \approx 30$) have the strongest segregation inside the viscous sublayer, because for them inhabitation of offspring vortices is most effective. While the effects of the near-wall structures are obviously significant, it is however worthwhile mentioning that some studies have demonstrated accumulation of particles in low-turbulence regions in flows without near-wall quasi-coherent structures, see e.g. Iliopoulos et al. (2003), Skartlien (2007), and Arcen and Tanière (2009), indicating that the near-wall turbulent structures may not be the direct cause of near-wall segregation.

Most studies on particle dispersion in wall-bounded flows have focused on the near-wall quasi-coherent turbulent structures, and very few paid attention to the influences of the Large-Scale Structures (LSSs) in the core region commonly encountered in some flows (Bernardini et al., 2013). For example, LSSs are observed in pipe and channel flows at high Re_τ (Kim and Adrian, 1999), but DNSs of particle-laden turbulent P flows at high Re_τ are still impracticable due to extensive computational cost (the highest Re_τ ever reported is $Re_\tau = 1000$ by Bernardini, 2014). However LSSs can be observed in a turbulent Couette flow (C flow) even at low or moderate Re_τ, which thus serves as a good background flow to evaluate the effects of LSSs on particle dispersion. In a C flow the two walls have a relative velocity which drives the in-between fluid. Turbulent C flows have coexisting turbulent streaks near the walls and the LSSs in the core region which interact with each other non-linearly (Kitoh et al., 2005; Bech et al., 1995). Although these interactions have crucial effects on particle dispersion, relevant studies are rare (Bernardini et al., 2013; Richter and Sullivan, 2013, 2014). One example to mention here is Bernardini et al. (2013), who conducted DNS coupled with Lagrangian particle tracking for a C flow at $Re_\tau = 167$ and compared with a P flow at $Re_\tau = 183$. They found the highest near-wall segregation at $St = 25$ for both the C flow and the P flow. Streamwise particle streaks were observed in the near-wall region for both flows, but the characteristic patterns of the streaks were essentially different, as a result of imprinting of the outer-layer LSSs onto the inner-layer fluid structures. While the C flow is a good choice for evaluating particle distribution under the influences of LSSs, the existence of near-wall structures makes it difficult to isolate the effects of LSSs in the near-wall region.

A combined turbulent C and P flow, namely the turbulent Couette–Poiseuille flow (CP flow), is a more computationally affordable prototype for evaluating the LSSs in wall-bounded flows (Kuroda et al., 1995; Pirozzoli et al., 2011; Yang et al., 2017). Compared to a C flow, the CP flow requires a smaller domain than that needed for a C flow (Bech et al., 1995; Tsukahara et al., 2006), since the LSSs generated in the core region is shorter in streamwise direction than those formed in a C flow (Pirozzoli et al., 2011). The CP flow has two controlling parameters, i.e. both a streamwise pressure gradient and a relative wall motion. In particular, with a carefully chosen combination of the controlling parameters, the mean shear and thus the turbulent regeneration events can be eliminated at one wall (Pirozzoli et al., 2011; Coleman et al., 2017; Yang et al., 2017). Due to the distinguishing near-wall structures at the opposing walls and also the presence of LSSs in the core region, the zero-mean-shear CP flow is a useful flow vehicle to explore individually the influences of both the near-wall streaks and the LSSs on particle distribution in turbulence. The CP flow is of theoretical importance, for example, it was used by Thurlow and Klewicki (2000) to understand the mechanisms of drag reduction at ultra-hydrophobic surfaces, and by Coleman et al. (2017) to improve turbulence closure models. In practice, the CP flow resembles the flow beneath a ship operating at small underkeel clearance (Gourlay, 2006).

It is worthwhile to point out a flow similar to the zero-mean-shear CP flow, i.e. the open-channel or free-surface flow. Studies on open-channel flows (Pan and Banerjee, 1995; van Haarlem et al., 1998; Narayanan et al., 2003; Nagaosa and Handler, 2003; Righetti and Romano, 2004) are inspiring for studies on the current CP flow due to some similarities in these two flows at first sight: both flows have asymmetric flow structures near the two opposing surfaces, and the near-wall quasi-coherent turbulent structures are observed only near the wall with maximum mean shear while they are absent near the shear-free surface. The asymmetric near-wall flow structures cause variation of the near-wall particle segregations for the two walls in an open-channel flow (van Haarlem et al., 1998; Narayanan et al., 2003). However, the boundary conditions at the shear-free surface are different in these two flows (no-slip for CP flow and free-slip for open-channel flow). Thus the wall-normal distributions of the turbulence intensities and the r.m.s. vorticity are distinctly different near this wall (Nagaosa and Handler, 2003; Yang et al., 2017). More importantly, the large scales observed in the two flows are essentially different. In an open-channel flow, the large-scale upwellings and downwellings in the bulk of flow are caused by the large-scale near-wall sweeps and ejections imprinting from near the no-slip wall to the free-slip wall. On the contrary, in the current CP flow sweep and ejection events are relatively small-scale and confined near the stationary wall like in a P flow. The longitudal LSSs that we observe in a CP flow at low Re_τ are large-scale streamwise circulations which are not present in an open-channel flow at a similar Re_τ.

It is our prime interest to investigate wall-normal particle segregation under the effects of the surrounding fluid (particularly the LSSs) and particle inertia. A specific turbulent CP flow with zero mean wall shear at the moving wall is considered, which enables us to investigate the influences of the LSSs on near-wall particle behaviors without the influence of near-wall turbulent struc-