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Turbulence Modulation by Micro-Particles in Boundary Layers

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Summary. Turbulent dispersed flows over boundary layers are crucial in a number of industrial and environmental applications. In most applications, the key information is the spatial distribution of inertial particles, which is known to be highly non-homogeneous and may exhibit a complex pattern driven by the structures of the turbulent flow field. Theoretical and experimental evidence shows that fluid motions in turbulent boundary layers are intermittent and have a strongly organized and coherent nature represented by the large scale structures. These structures control the transport of the dispersed species in such a way that the overall distribution will resemble not at all those given by methods in which these motions are ignored.

In this paper, we study from a statistical viewpoint turbulence modulation produced by different-size dispersed particles and we examine how particle wall accumulation is modified due to the action of particles themselves in modulating turbulence. The physical mechanisms and the statistics proposed are based on Direct Numerical Simulation of turbulence and Lagrangian particle tracking, considering a two-way coupling between particles and fluid.

1.1 Introduction

In a number of environmental and industrial problems involving turbulent dispersed flows, the information on particle distribution is a crucial issue. In particular, the relevant information sought is the local concentration of particles which controls all relevant exchange mechanisms (e.g. momentum exchange, reaction and deposition rates, mass transfer, evaporation, etc.). Accurate three-dimensional, time-dependent simulations together with precise experiments are required to gain physical insights on the effect of the flow on particles distribution and of particles on the flow field. The simplest computational approach to investigate on dispersed flows is to consider particles as passive species under the one-way coupling assumption, which is valid for dilute flows characterized by volume fraction $\Phi_V < 10^{-3}$ and mass fraction $\Phi_M < 10^{-3}$ [1, 2].

Simulations performed under dilute flow conditions have shown that turbulent flow fields in general are of a strongly organized and coherent nature represented by large scale structures. These structures, because of their coherence and persistence, have a significant influence on the transport of dispersed particles. Specifically, coherent structures generate preferentially directed, non-random motion of particles leading to non-uniform concentration and to long-term accumulation. The effect of local spatial structures of the flow field on particles is related to their mutual interaction which, in turn, is modulated by inertia [3, 4, 5] and their action is not captured by engineering models [6, 7, 8].

Preferential accumulation of particles induced by turbulence coherent structures has been examined previously in a number of theoretical and experimental works [3, 4, 5, 9, 10, 11]. In the case of homogeneous turbulence [3, 4, 5, 11], the particle concentration field will be characterized by local particle accumulation in low-vorticity, high-strain regions. In the case of non-homogeneous turbulence [9, 10], the local interaction between particles and turbulence structures produce a remarkably macroscopic behavior leading to long-term particle accumulation in the viscous sublayer [12, 13, 14]. When particles segregate in specific flow regions, the dilute flow assumption is no longer valid locally. In particular, if particles are heavy (solid/liquid in gas), their overall volume may be negligible, yet the momentum coupling with the fluid may be such to induce significant modifications in the flow field [2, 15, 16, 17]. These effects will modify flow transport properties which eventually will change particle distribution. This may be of fundamental significance in applications as particle abatement, flow reactors and control of momentum, heat and mass fluxes at a wall.

In this paper, we examine from a statistical viewpoint the two-way interaction between particles and fluid in non-homogeneous turbulence. In particular, we aim at studying turbulence modifications due to particles having different inertia when gravity is neglected. The mean interparticle spacing, even for clustering particles, was $O(10)$ so in this work we also neglected the particle-particle interactions [18].

1.2 Methodology

The balance equations governing the turbulent channel flow are (in dimensionless form):

$$\frac{\partial u_i}{\partial x_i} = 0 \ , \tag{1.1}$$

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} + \frac{1}{Re_\tau} \frac{\partial^2 u_i}{\partial {x_j}^2} - \frac{\partial p}{\partial x_i} + \delta_{1,i} + \tilde{\mathbf{f}}_{2w} \ , \tag{1.2}$$

where u_i is the i^{th} component of the velocity vector, p is the fluctuating kinematic pressure, $\delta_{1,i}$ is the mean pressure gradient driving the flow, Re_τ is the shear Reynolds number, while $\tilde{\mathbf{f}}_{2w}$ is an equivalent body force accounting for the action of the dispersed particles onto the fluid ($\tilde{\mathbf{f}}_{2w} = 0$ for simulations run under the one-way coupling assumption). For a generic volume of fluid Ω_p containing a particle, the action-reaction law imposes that:

$$\int_{\Omega_p} \tilde{\mathbf{f}}_{2w}(\mathbf{x})\; d\Omega = -\mathbf{f}_{fl}\ , \tag{1.3}$$

where $\mathbf{f}_{fl}$ is the force exerted on the particles by the fluid. The term $\tilde{\mathbf{f}}_{2w}$ can be obtained by adding the contributions of each particle:

$$\tilde{\mathbf{f}}^k_{2w} = \sum_{p=1}^{n_p} \left(\mathbf{f}^k_{2w}\right)_p\ , \tag{1.4}$$

where n_p is the number of particles. With the point-source approximation [15, 19], $\mathbf{f}_{2w}(\mathbf{x}) = -\mathbf{f}_{fl}\ \delta(\mathbf{x} - \mathbf{x}_p)$, where $\delta(\mathbf{x})$ is the Dirac's delta function.

Equations. (1.1) and (1.2) are solved using pseudo-spectral Direct Numerical Simulation (DNS): details of the numerical method can be found elsewhere [20].

Particle motion is described by a set of ordinary differential equations for particle velocity and position. For particles much heavier than the fluid ($\rho_p/\rho \gg 1$, where ρ_p is particle density and ρ is fluid density), the only significant forces are Stokes drag and buoyancy, whereas Basset force can be neglected being an order of magnitude smaller [21]. The effects of gravity and shear-induced lift have also been neglected for the sake of improving fundamental understanding of two-way coupling with a manageable parameter range. With the above simplifications the following Lagrangian equation for the particle velocity is obtained [22]:

$$\frac{d\mathbf{v}}{dt} = -\frac{3}{4}\frac{C_D}{d_p}\left(\frac{\rho}{\rho_p}\right)|\mathbf{v} - \mathbf{u}|(\mathbf{v} - \mathbf{u})\ , \tag{1.5}$$

where $\mathbf{v}$ and $\mathbf{u}$ are the particle and fluid velocity vectors, d_p is particle diameter. The drag coefficient C_D is given by:

$$C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687})\ , \tag{1.6}$$

where the particle Reynolds number is equal to $Re_p = d_p|\mathbf{v} - \mathbf{u}|/\nu$, ν being fluid kinematic viscosity. Correction for C_D is necessary since Re_p does not necessarily remain small, in particular for depositing particles.

1.3 Numerical Simulations

The flow into which particles are introduced is a turbulent Poiseuille channel flow of air ($\rho = 1.3\ kg/m$, $\nu = 15.7 \cdot 10^{-6} m^2/s$) assumed incompressible and

$\tau_p^+ (=St)$	d_p^+	ρ_p^+	v_{sett}^+	Φ_V	Φ_M	n_p	ΔT_p^+
1.0	0.153	769.23	0.0942	$3.52 \cdot 10^{-7}$	$2.71 \cdot 10^{-4}$	10^5	1080
5.0	0.342	769.23	0.4710	$3.93 \cdot 10^{-6}$	$3.02 \cdot 10^{-3}$	10^5	1080
25.0	0.765	769.23	2.3350	$4.40 \cdot 10^{-5}$	$3.38 \cdot 10^{-2}$	10^5	1080

Table 1.1. Parameters relative to the simulation of particle dispersion. The superscript + identifies dimensionless variables: particle relaxation time τ_p^+ (equivalent to particle Stokes number St), particle density ρ_p^+, particle diameter d_p^+ and particle settling velocity v_{sett}^+. Φ_V and Φ_M represent the average volume fraction and the average mass fraction of the particles, respectively.

Newtonian. The reference geometry consists of two infinite flat parallel walls: the origin of the coordinate system is located at the center of the channel and the $x-$, $y-$ and $z-$axes point in the streamwise, spanwise and wall-normal directions respectively. Periodic boundary conditions are imposed on the fluid velocity field in x and y, no-slip boundary conditions are imposed at the walls. All variables are normalized by the wall shear velocity u_τ, the fluid kinematic viscosity ν and the half channel height h. The shear velocity is defined as $u_\tau = (\tau_w/\rho)^{1/2}$, where τ_w is the mean shear stress at the wall. Calculations are performed on a computational domain of $1885 \times 942 \times 300$ wall units in x, y and z discretized with $128 \times 128 \times 129$ nodes. The shear Reynolds number is $Re_\tau = u_\tau h/\nu = 150$. The time step used is $\Delta t^+ = 0.045$ in wall time units.

A Lagrangian particle tracking code coupled with the DNS code was developed to calculate particles paths in the flow field. The code interpolates fluid velocities at Eulerian grid nodes onto the particle position by means of 6^{th} order Lagrangian polynomials, and integrates the equations of particle motion forward in time by means of a 4^{th} order Runge-Kutta scheme. Four sets of 10^5 particles were considered, characterized by different values of the relaxation time, defined as $\tau_p = \rho_p d_p^2/18\mu$ where μ is the fluid dynamic viscosity. Particle relaxation time is made dimensionless using wall variables and the Stokes number for each particle set is obtained. In this work, we considered $\tau_p^+ = St = 1$, 5 and 25, as shown in Table 1.1 which summarizes all relevant simulation parameters.

At the beginning of the simulation, particles are distributed homogeneously over the computational domain and their initial velocity is set equal to that of the fluid at particle position. Also, particles are assumed to be pointwise, rigid and spherical. Periodic boundary conditions are imposed on particles in both streamwise and spanwise directions, elastic reflection is applied when the particle centre is a distance less than $d_p/2$ from the wall. Elastic reflection was chosen since it is the most conservative assumption when studying the particle prefential concentration in a turbulent boundary layer. Interparticle collisions are neglected.

1.4 Results

1.4.1 Flow Field Modification by Particles

Object of this paper is to study the modification of turbulence due to the two-way interaction between fluid and particles having different inertia in the absence of gravity. In this section, we will compare results obtained from two-way coupling simulations with available results from previous one-way coupling simulations [23], in which particles are not allowed to influence the fluid motion $-\tilde{\mathbf{f}}_{2w} = 0$ in Equation (1.2). Similar studies have been performed previously for the case of homogeneous isotropic turbulence [21, 24].

The effect of particles with different inertia on the streamwise component $< u_x^+ >$ of the mean fluid velocity is shown in Fig. 1.1a, where lines refer to benchmark one-way coupling simulations and symbols refer to two-way coupling simulations accounting for particle feedback on turbulence. We do not show the spanwise and the wall-normal components of the mean fluid velocity since they exhibit the expected behavior and do not add to the discussion. Velocity profiles, averaged in both space (over the streamwise and spanwise directions) and time (over a time span of 1080 t^+) and normalized by the shear velocity u_τ of the particle-free flow, deviate only slightly, if not negligibly, from each other. Deviations correspond to reductions of the channel flowrate no larger than 0.4 % with respect to one-way coupling simulations. A careful examination of Fig. 1.1a indicates that velocity profiles computed under two-way coupling conditions are slightly shifted towards higher values in the buffer region ($5 < z^+ < 30$) and towards smaller values in the outer region ($z^+ > 30$).

More noticeable differences are observed for turbulence intensities (RMS of fluid velocity fluctuations), whose streamwise, spanwise and wall-normal components are shown in Figs. 1.1b, 1.1c and 1.1d, respectively. As in Fig. 1.1a, lines refer to one-way coupling simulations whereas symbols refer to two-way coupling simulations. It appears that particles do not affect much turbulence intensities in the outer flow but, for both the spanwise component ($< {u'_{y,rms}}^+ >$ in Fig. 1.1c), and the wall-normal component ($< {u'_{z,rms}}^+ >$ in Fig. 1.1d) and regardless of particle size, they do substantially increase them at the wall, particularly in the region where profiles develop a peak. Conversely a decrease in the RMS along the streamwise direction ($< {u'_{x,rms}}^+ >$, Fig. 1.1b) is observed in correspondence of the maximum values.

The modifications in the RMS is likely to cause a modification in heat and mass transfer since the wall-normal velocity fluctuations are responsible for transport processes at the wall [25].

The Reynolds stress profiles, shown in Fig. 1.2 for one-way coupling (line) and two-way coupling simulations (symbols), do show modifications due to particles outside the viscous wall region. The effect of particles is noticeable in the buffer layer, where the Reynolds stresses increase. The Reynolds stresses in the very-near-wall region ($z^+ < 5$ roughly) do not exhibit significant changes.

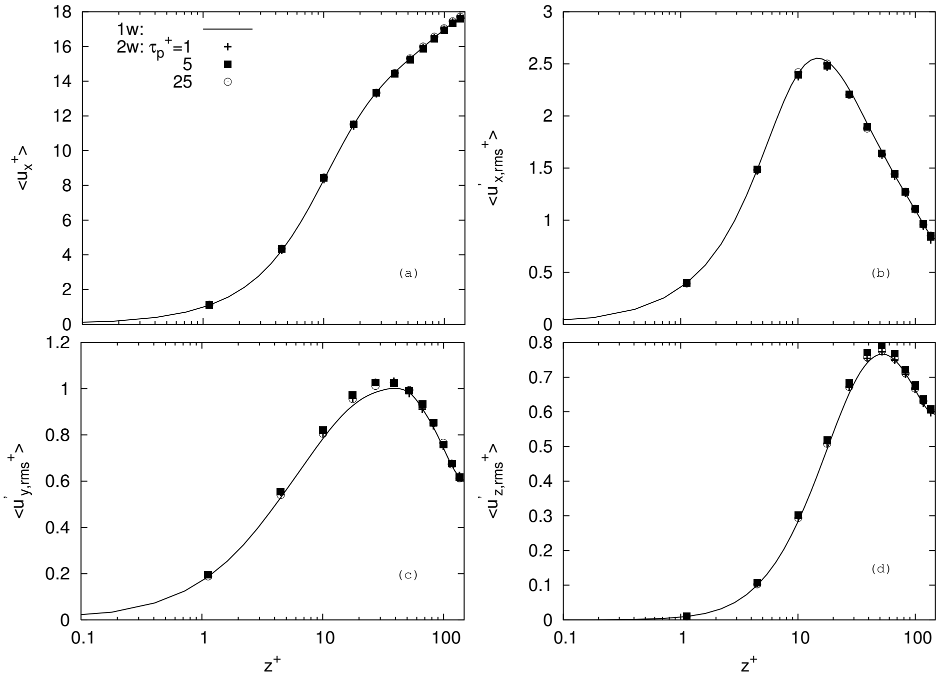

Fig. 1.1. Mean and RMS fluid velocity profiles for one-way coupling (lines) and two-way coupling (symbols).

1.4.2 Influence of Flow Field Modification on Particle Statistics

The issue addressed in this section is: how turbulence modulation by particles influences the distribution of the particles? We will try to answer this question by comparing results on particle statistics obtained from simulations with and without particle feedback on turbulence.

Fig. 1.3 shows the streamwise ($< v_x^+ >$) and the wall-normal ($< v_z^+ >$) components of the mean particle velocity for one-way coupling (solid line with empty circles) and two-way coupling (black circles) simulations. Figs. 1.3a and 1.3b are relative to $\tau_p^+ = 1$ particles, Figs. 1.3c and 1.3d are relative to $\tau_p^+ = 5$ particles, Figs. 1.3e and 1.3f are relative to $\tau_p^+ = 25$ particles. Modifications to the mean streamwise velocity are pretty small: profiles shown in Figs. 1.3a, 1.3c and 1.3e overlap almost perfectly regardless of particle size, and only slight deviations can be observed for the larger particles two-way coupled with the fluid.

More noticeable (and meaningful) differences are observed for the wall-normal velocity, shown in Figs. 1.3b, 1.3d and 1.3f. Under the one-way coupling assumption, profiles of particle wall-normal velocity develop a peak in the buffer layer, which increases monotonically with particle inertia. Corre-

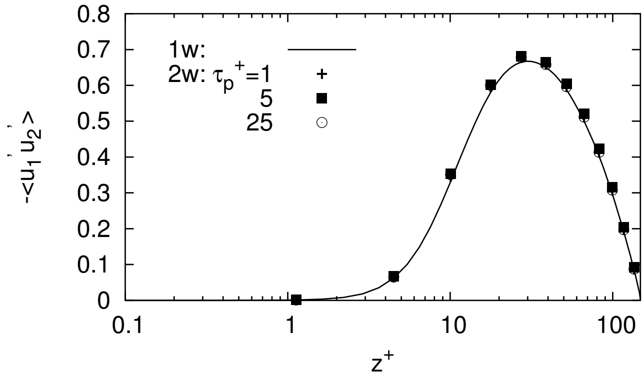

Fig. 1.2. Reynolds stress for one-way coupling (lines) and two-way coupling (symbols).

spondingly, particle wall-normal turbophoretic accumulation increases with particle inertia. A two-way coupling between particles and fluid appears to modify the shape of the profiles from a quantitative (though not qualitative) viewpoint by shifting them towards smaller values for $\tau_p^+ = 1$ and 25 and to larger values for $\tau_p^+ = 5$.

Results on second-order moments for the particle velocity field (not shown) provide evidence that RMS velocity fluctuations are not much affected by the two-way coupling in the outer region and slightly increase near the wall. The behavior qualitatively resembles that of the fluid flow field (see Fig. 1.1).

Fig. 1.4 shows the time evolution of particle concentration profiles along the wall-normal direction, for $\tau_p^+ = 1$ particles (Fig. 1.4a), $\tau_p^+ = 5$ particles (Fig. 1.4b) and $\tau_p^+ = 25$ particles (Fig. 1.4c), respectively. Lines with empty symbols refer to one-way coupling simulations, whereas black symbols refer to two-way coupling simulations. Profiles are averaged in space (along the streamwise and spanwise directions), smoothed by time-averaging over spans of 360 time units and normalized with respect to the initial uniform concentration. It is apparent that particle interactions with turbulence act to decrease the near-wall peak of concentration. This behavior is in agreement with the decrease of particle drift velocity in the wall-normal direction previously observed in Fig. 1.3b,f for $\tau_p^+ = 1$ and 25. Surprisingly, this is not the case for $\tau_p^+ = 5$ for which, despite of a larger wallward wall-normal velocity, the peaks of accumulation are also reduced with two-way coupling. This effect is more evident for the smaller particles ($\tau_p^+ = 1$, Fig. 1.4a) and increases monotonically with particle inertia.

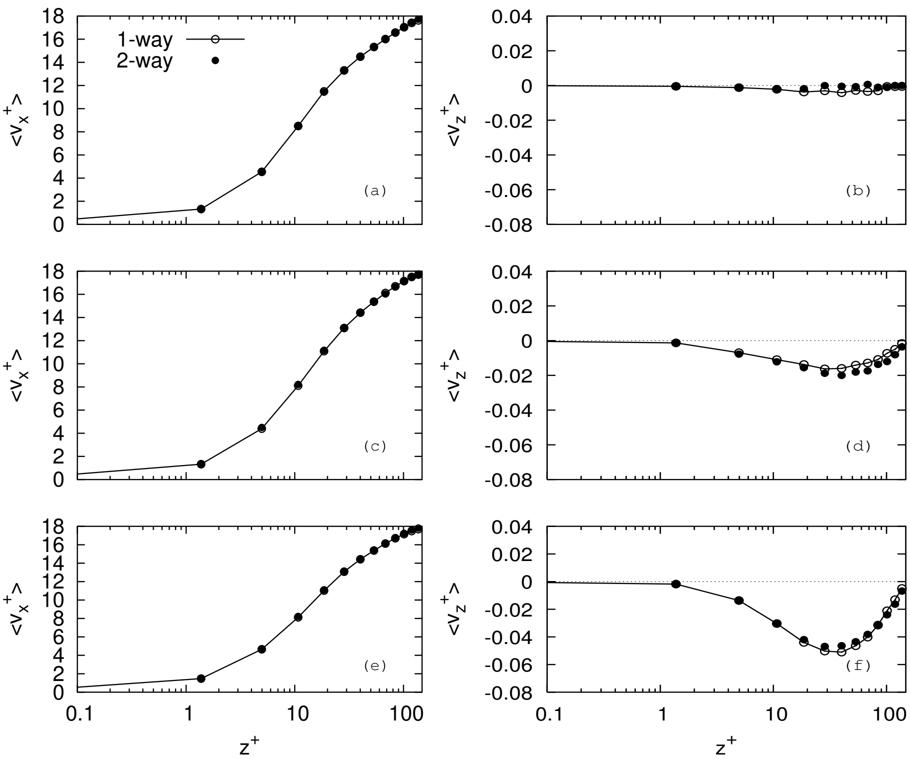

Fig. 1.3. Streamwise ($< v_x^+ >$) and wall-normal ($< v_z^+ >$) components of mean particle velocity for one-way coupling (solid line with empty circles) and two-way coupling (black circles). (a) and (b) $\tau_p^+ = 1$, (c) and (d) $\tau_p^+ = 5$, (e) and (f) $\tau_p^+ = 25$.

1.5 Concluding Remarks

This paper addresses the issue of particle preferential concentration in a fully developed turbulent boundary layer with specific reference to the influence of particle inertial response to the underlying flow field under one-way and two-way coupling assumptions.

Statistical analysis of particle and fluid velocity fields computed from numerical simulations run under dilute flow conditions provides evidence of the crucial effect of inertia in determining particle drift toward the wall and particle sampling of specific flow regions: as a consequence, particles accumulate in the near-wall region, this trend being enhanced by increasing particle inertia.

When particles segregate in specific flow regions, the effect of the dispersed phase on turbulence is no longer negligible and the dilute flow assumption is not valid locally. Simulations with a two-way coupling between particles and fluid were performed to investigate on turbulence modifications due to dispersion and segregation of particles with different inertia in the flow. For the particle sizes investigated in this work, turbulence modulation by particles

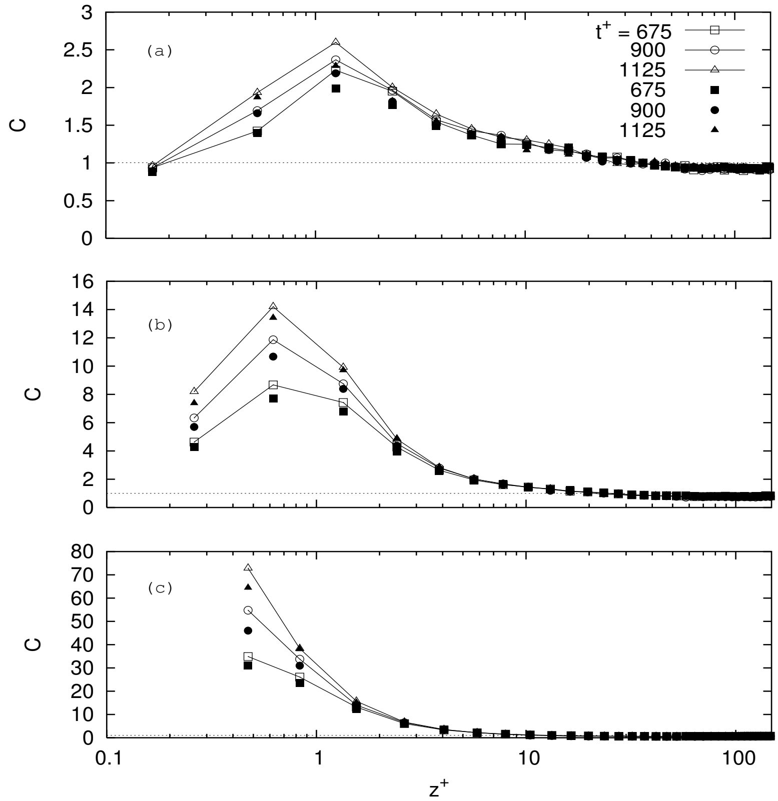

Fig. 1.4. Time evolution of particle concentration profiles along the wall-normal direction for one-way coupling (lines with empty symbols) and two-way coupling (black symbols) simulations. (a) $\tau_p^+ = 1$, (b) $\tau_p^+ = 5$, (c) $\tau_p^+ = 25$.

appears rather small. This may be due to the small volume fraction occupied by the particles and to the fact that only the effect of the drag force was considered in the balance equation of particle motion. However, it was possible to observe that particle accumulation in the near-wall region is overestimated when the feedback of the dispersed phase onto the flow field is neglected.

Further developments of this work will be the inclusion of the gravitational effect and the lift force in the balance equation of particle motion. Another issue is the singular effect of the particle time-scale which can be also studied by fixing the volume fraction and varying particle size.

References

1. W.S. Uijttewaal & R.V.A. Oliemans, Particle dispersion and deposition in direct numerical and large eddy simulations of vertical pipe flows, *Phys. Fluids*, vol.

8, pp. 2590-2604, 1996.

2. K.T. Kiger & C. Pan, Suspension and turbulence modification effects of solid particulates on a horizontal turbulent channel flow, *Journal of Turbulence*, vol. 3, pp. 1-21, 2002.
3. L.P. Wang & M.R. Maxey, Settling velocity and concentration distribution of heavy particles in homogeneous isotropic turbulence, *J. Fluid Mech.*, vol. 256, pp. 27-68, 1993.
4. M.W. Reeks, On the dispersion of small particles suspended in an isotropic turbulent fluid. *J.Fluid Mech.*, vol. 83, pp. 529-546, 1977.
5. M.R. Maxey, The gravitational settling of aerosol particles in homogeneous turbulence and random flow fields, *J. Fluid Mech.*, vol. 174, pp. 441-465, 1987.
6. S.E. Elghobashi & T.W. Abou Arab, A two equation turbulence model for two-phase flows, *Phys. Fluids*, vol. 26, pp. 931-938, 1983.
7. J. Young & A. Leeming, A theory of particle deposition in turbulent pipe flow, *J. Fluid Mech.* , vol. 340, pp. 129-159, 1997.
8. S., Cerbelli, A., Giusti & A. Soldati, ADE approach to predicting dispersion of heavy particles in wall bounded turbulence, *Int. J. Multiphase Flow*, vol. 27, pp. 1861-1879.
9. M. Caporaloni, F. Tampieri, F. Trombetti & O. Vittori, Transfer of particles in nonisotropic air turbulence, *J. Atmos. Sci.*, vol. 32, pp. 565-568, 1975.
10. M.W. Reeks, The transport of discrete particles in inhomogeneous turbulence, *J. Aerosol Sci.*, vol. 310, pp. 729-739, 1983.
11. J.K. Eaton & J.R. Fessler, Preferential concentration of particles by turbulence, *Intl J. Multiphase Flow*, vol. 20, pp. 169-209, 1994.
12. C. Marchioli & A. Soldati, Mechanisms for particle transfer and segregation in turbulent boundary layer, *J. Fluid Mech.*, vol. 468, pp. 283-315, 2002.
13. C. Marchioli, A. Giusti, M.V. Salvetti & A. Soldati, Direct numerical simulation of particle wall transfer and deposition in upward turbulent pipe flow, *Int.J.Multiphase Flow*, vol. 29, pp. 1017-1038, 2003.
14. C. Narayanan, D. Lakehal L. Botto & A. Soldati, Mechanisms of particle deposition in a fully developed turbulent channel flow, *Phys. Fluids A*, vol. 15, pp. 763-775, 2003.
15. M. Boivin, O. Simonin & K.D. Squires, Direct numerical simulation of turbulence modulation By particles in isotropic turbulence, *J. Fluid Mech.*, vol. 375, pp. 235-263, 1998.
16. A.A. Mostafa & H.C. Mongia, On the interaction of particles and turbulent fluid flow, *Int. J. Heat Mass Transfer*, vol. 31, pp. 2063-2075, 1988.
17. S. Dasgupta, R. Jackson & S. Sundaresan, Gas-particle flow in vertical pipes with high mass loading of particles, *Powder Technology*, vol. 96, pp. 6-23, 1998.
18. C. Crowe, M. Sommerfeld & Y. Tsuji, Multiphase flows with droplets and particles, CRC Press, New York, 1998.
19. S. Sundaram & L.R. Collins, A numerical study of the modulation of isotropic turbulence by suspended particles, *J. Fluid Mech.*, vol. 379, pp.105-143, 1999.
20. K. Lam & S. Banerjee, On the condition of streak formation in bounded flows, *Phys. Fluids A*, vol. 4, pp. 306-320, 1992.
21. S. Elghobashi & G.C. Truesdell, Direct simulation of particle dispersion in a decaying isotropic turbulence, *J. Fluid Mech.* , vol. 242, pp. 655-700, 1992.
22. M.R. Maxey & J.K. Riley, Equation of motion for a small rigid sphere in a nonuniform flow, *Phys. Fluids A* , vol. 26, pp. 883-889, 1983.

23. M. Picciotto, C. Marchioli, M. Reeks & A. Soldati, Statistics of velocity and preferential accumulation of micro-particles in boundary layer turbulence, *Nucl. Eng. & Design*, In Press, 2005.
24. O.A. Druzhinin, The influence of particle inertia on the two-way coupling and modification of isotropic turbulence by microparticles. *Phys. Fluids*, vol. 13, pp. 3738-3755, 2001.
25. D. Kaftori, G. Hetsroni & S. Banerjee, The effect of particle on wall turbulence, *Int. J. Multiphase Flow*, vol. 24, pp. 359-386, 1998.