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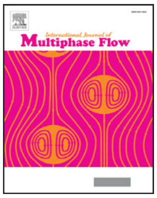

# Direct numerical simulation of a particle-laden flow in a flat plate boundary layer

Dong Li, Anyang Wei, Kun Luo, Jianren Fan*

*State Key Laboratory of Clean Energy Utilization, Zhejiang University, 38 Zheda Road, Hangzhou 310027, PR China*

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ABSTRACT

In this paper, a direct numerical simulation of particle-laden flow in a flat plate boundary layer is performed, using the Eulerian–Lagrangian point-particle approach. This is, as far as we know, the first simulation of a particle-laden spatially-developing turbulent boundary layer with two-way coupling. A local minimum of the particle number density is observed in the close vicinity of the wall. The present simulation results indicate that the inertial particles displace the quasi-streamwise vortices towards the wall, which, in turn, enhance the mean streamwise fluid velocity. As a result, the skin-friction coefficient is increased whereas the boundary layer integral thicknesses are reduced. The presence of particles augments the streamwise fluctuating velocity in the near-wall region but attenuates it in the outer layer. Nevertheless, the wall-normal and spanwise velocity fluctuations are significantly damped, and so is the Reynolds stress. In addition, the combined effect of a reduced energy production and an increased viscous dissipation leads to the attenuation of the turbulent kinetic energy.

## Introduction

Boundary layers are ubiquitous in a great number of natural flows and fluid dynamics engineering applications, such as the earth's atmosphere, the surface of car, ship and air vehicles, etc. The particle-laden flow in a zero-pressure-gradient flat plate boundary layer (ZPGFPBL) is of great importance in a number of engineering and environmental applications. For example, the interactions between volcanic ash particles and blade in the turbines of aircraft engines may damage the turbine blade and even destroy the commercial aircraft (Grindle and Burcham, 2003); the interactions between sand and helicopters may pose a potential hazard to the safety of helicopters (Jasion and Shrimpton, 2012). In addition, the dispersion of contaminants along the land or sea is also a typical example of particle-laden turbulent flow. Studying the interactions between the particulate matter and the atmosphere may help to control and reduce pollution. The spatially developing single-phase ZPGFPBL has been investigated numerically and experimentally for many years, however, there is few detailed research report about the particle-laden ZPGFPBL in the literature.

A great deal of experimental research has been carried out in an attempt to study the single-phase ZPGFPBL. Liu and Rodi (1991) used hot-wire measurements to study the spatially developing boundary layer along a flat plate. Their experimental results showed that the completion of transition in the outer region of the boundary layer lagged behind the near-wall region. Adrian et al. (2000) studied experimentally the structure of energy-contain turbulence in the outer region of a ZPGFPBL using particle image velocimetry. They observed that hairpin vortices occurred in streamwise-aligned packets in the outer region of the turbulent boundary layer. Recently, Vincenti et al. (2013) investigated experimentally the statistical properties of ZPGFPBL with high Reynolds number. In addition, the ZPGFPBL has also been studied by a great number of numerical simulations during the last two decades. Spalart (1988) exploited a direct numerical simulation (DNS) of ZPGFPBL using a spectral method. A systematic multiple-scale procedure was used to approximate the slow streamwise growth of the boundary layer. Their simulation results have become a standard reference for numerical simulation of ZPGFPBL. Wu and Moin (2009) simulated a nominally ZPGFPBL from laminar, transitional to turbulent flow. They firstly observed populated hairpin forest vortices throughout both the transitional and the turbulent regions. Schlatter et al. (2009) performed DNSs and experiments of a spatially developing turbulent boundary layer up to Reynolds number $Re_\theta = 2500$. A "fringe-region" was added at the end of the computational domain to satisfy the periodic boundary conditions in the streamwise direction. Their numerical results clearly showed that the boundary layer was dominated by large-scale turbulent structures with sizes on the order of the boundary layer thickness. Soon after, a decoupling procedure based on the Hilbert transformation was employed to quantify the interactions between large and small scales in wall-bounded turbulent flows by Schlatter and Örlü (2010).

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* Corresponding author. Tel.: +86 0571 87951764; fax: +86 0571 87951764.
*E-mail address:* fanjr@zju.edu.cn (J. Fan).

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Marusic et al. (2010) pointed out that the near-wall region in the flat plate boundary layer was usually beyond the scrutiny of experimental measurement techniques and remained largely undocumented. More recently, Borrell et al. (2013) developed a new high-resolution code to simulate a ZPGFPBL from $Re_\theta = 300$ to 6800, which is, up to now, the highest Reynolds number reached in DNS of a ZPGFPBL.

Concerning the particle-laden turbulent flows, a lot of experiments and numerical simulations have been performed during the past few decades with a variety of different motivations. Kaftori et al. (1995) investigated experimentally the motion of solid particles near the wall in a turbulent boundary layer by flow visualization techniques and laser Doppler anemometry. Their experimental results showed that the coherent wall structures controlled the particle motion, entrainment and deposition process. Liu and Rodi (1991) firstly exploited a DNS of particle-laden turbulent flow in a three-dimensional time-dependent vertical channel flow and found that particles tended to accumulate in the viscous sublayer by inward turbulent motions, i.e. sweep event. Marchioli and Soldati (2002) examined the particle behaviours in a vertical channel flow via a pseudo-spectral approach. Their simulation results confirmed that sweeps and ejections are efficient transfer mechanisms for particles. Recently, Sardina et al. (2012) performed a DNS of a particle-laden spatially developing turbulent boundary layer with one-way coupling. They found that the particle concentration and the streamwise velocity profiles were self-similar and depended only on the local outer Stokes number and the rescaled wall-normal distance.

As particle mass loading increases, the effect of particles on fluid can no longer be ignored. Tsuji and Morikawa (1982) used laser Doppler velocimeter to measure the air and particle velocities in a horizontal pipe. They concluded that large particles increased the turbulence intensity whereas small particles decreased it. Righetti and Romano (2004) studied experimentally the dynamical interactions between solid particles and fluid in a turbulent open channel flow over a smooth bed. They observed that both the streamwise mean velocities of particles and fluid were reduced in the outer layer whereas increased in the viscous sublayer. In addition, the streamwise and vertical turbulence intensities were attenuated in the outer layer, but augmented in the very near-wall region. In the two-way coupled DNS, Elghobashi and Truesdell (1993), Boivin et al. (1998) and Sundaram and Collins (1999) focused on the turbulence modulation by particles in homogeneous isotropic turbulence. Elghobashi and Truesdell (1993) reported that the particles increased the fluid energy at high wave numbers. Boivin et al. (1998) observed an increased dissipation of the kinetic energy of the fluid in the presence of particles with higher mass loadings. Sundaram and Collins (1999) found that both the viscous and drag dissipations were enhanced due to the presence of inertial particles. Portela and Oliemans (2003) developed a code for DNS of particle-laden turbulent flows, using an Eulerian–Lagrangian point-particle method. Their results suggested that the behaviour of wall-bounded particle-laden flows can be understood in terms of the interactions between the particles and the streamwise vortices. When considered the two-way coupling effects, the inertial particles produced a large damping in the intensity of the streamwise vortices, without any substantial change in their shape and size. A review of the experimental and numerical studies of the turbulent dispersed multiphase flows was presented by Balachandar and Eaton (2010). Gualtieri et al. (2013) studied the particle clustering under two-way coupling regime and the turbulence modulation by DNS of a particle-laden homogeneous shear flow. Their new findings have a certain impact on the turbulent modelling of multiphase flows. More recently, a new methodology, which was able to capture the interphase momentum exchange between fluid and particles in the turbulent flow, was proposed by Gualtieri et al. (2015). This approach overcomes several drawbacks of established methods, like the classical particle in cell (PIC) method introduced by Crowe et al. (1977), and can be applied in a highly efficient computational algorithm.

Despite several decades of extensive numerical and experimental investigations on particle-laden turbulent flows, however, it is extremely difficult to fully understand the particle dynamics in wall-bounded flows. In particular, the dispersion of particles and the effects of inertial particles on turbulence modulation are far from being understood. In addition, among these previous studies, the particle dynamics have been investigated mainly on homogeneous isotropic turbulent flows, and parallel flows such as channel or pipe flows. These are statistically homogeneous in the flow direction and the particle motion is assumed to be periodic. In the particle-laden ZPGFPBL, however, the flow is spatial developing and the particle motion is no longer periodic along the streamwise direction. It should be pointed out that, so far, it is nearly impossible to find a two-way coupled DNS of particle-laden ZPGFPBL in the literature. Given the importance of particle-laden turbulent boundary layer flow in the industrial and environmental applications, it is meaningful to perform a DNS of turbulent boundary layer laden with solid particles. The purpose of this work is to assess the interactions between the fluid turbulence and the inertial particles. In addition, we will try to establish a physical link between inertial particles and near-wall coherent structures in the turbulent boundary layer.

The paper is organized as follows. The numerical methodology is described in section “Numerical methodology”. Then in section “Results and discussion”, we present the results for DNS of a particle-laden turbulent flow with one-way and two-way coupling. The particle distribution in the flat plate boundary layer is demonstrated in section “Particle distribution in the boundary layer”. The statistics of the mean and fluctuating quantities in the two-way coupled particle-laden flow are presented and analyzed in section “Statistics in the particle-laden flow”. These statistics are carefully compared with the single-phase flow in order to reveal the effect of particles on turbulence modification in the ZPGFPBL. Finally, conclusions are drawn in section “Conclusions”.

## Numerical methodology

### *Fluid motion*

#### *Governing equations for fluid*

In the study, the gas phase fluid is assumed to be incompressible and Newtonian. Even though the direct influence of particles on the continuity equation is assumed negligible in view of a low particle volume fraction (less than $10^{-3}$), the effect on the fluid momentum is account for. Therefore, the continuity and momentum equations for the fluid in dimensionless form read as:

$$\nabla \cdot \mathbf{u} = 0, \tag{1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re_{\theta_0}} \nabla^2 \mathbf{u} + \mathbf{f}, \tag{2}$$

where $\mathbf{u} = (u, v, w)$ is the fluid velocity vector in Cartesian coordinates, $p$ is the fluid pressure. The momentum thickness Reynolds number at the inlet plane, $Re_{\theta_0}$, is defined based on the free stream velocity, $U_\infty$, the inlet-boundary-layer momentum thickness, $\theta_0$, and the kinematic viscosity, $\nu$. All variables in Eqs. (1) and (2) are non-dimensionalized by $U_\infty$ and $\theta_0$. $\mathbf{f}$ represents the feedback force in the control volume due to the presence of particles.

#### *Computational domain and boundary conditions*

Typically, the air with density $\rho = 1.205$ kgm$^{-3}$ and kinematic viscosity $\nu = 1.5 \times 10^{-5}\ m^2\, s^{-1}$ is considered in the present simulation. A schematic of the computational domain is illustrated in Fig. 1. The origin of the Cartesian coordinate system is located at the leading edge of the plate and the coordinates *x*, *y*, *z* refer to the streamwise, wall-normal and spanwise directions, respectively. The laminar