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Stochastic dispersion of ellipsoidal fibers in various turbulent fields

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ABSTRACT

In this study dispersion and deposition of fibers of various sizes in fully developed turbulent pipe and duct flows were analyzed for a range of flow Reynolds numbers. Fibers translational and rotational equations of motion were solved using the Lagrangian approach assuming one-way interaction. The influences of turbulent fluctuations were included using appropriate stochastic models for fluctuating velocity and velocity gradient components. Performance of the stochastic model was evaluated for several test cases including dispersion of fibers in a synthesized isotropic homogenous turbulent flow field, inhomogeneous turbulent flow field, and fully developed turbulent pipe and duct flows. The simulation results were compared with earlier numerical and experimental studies for flow statistics and deposition velocity and good agreements were observed. It was shown that using appropriate stochastic models leads to satisfactory evaluation of dispersion and deposition of fibers in turbulent flows.

1. Introduction

The physics of particle transport and deposition is important in many areas of fluid engineering. Fouling in heat exchangers, deposition of particulate pollutant in respiratory tract, transport and deposition of particles in microelectronics and paper industries are some examples. In the recent years, commercial CFD softwares for simulation of particle transport and deposition were developed, which typically assume that the particles are spherical. However, majority of the particles suspended in airflows are non-spherical and many are elongated fibers with large aspect ratios. The principal factors affecting transport and deposition pattern of fibers include aerodynamic properties of these particles, their size and aspect ratio, and the flow velocity field.

Several studies related to particle motion were reported in the literature. Using the concept of free flight, Friedlander and Johnstone (1957) developed a theory for particle deposition in turbulent flows. Ahmadi (1970) reported analytical and numerical simulations of dispersion of small suspended particles in turbulent flows. Reeks (1977) and Maxey (1987) studied the effect of crossing trajectories and gravitational settling on dispersion of particles. Ounis and Ahmadi (1989, 1990, 1991) conducted numerical simulations and reported theoretical models for diffusivity of particles in isotropic and turbulent shear flows. They noted the important role of shear-induced lift force on particle dispersion across a shear field. Cleaver and Yates

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(1975) studied the particle deposition mechanism due to turbulent burst and inrush. Further progress along this line were reported by Fichman et al. (1988), and Fan and Ahmadi (1993, 1994, 1995a, 1995b, 2000). Numerical simulations of particle deposition in laminar and turbulent duct flows were performed by Li and Ahmadi (1993), He and Ahmadi (1999), Zhang and Ahmadi (2000), Zhang et al. (2001), and Tian and Ahmadi (2007). More recently, Tian et al. (2012) had performed experimental and numerical studies to evaluate the motion of ellipsoidal fibers in low Reynolds number flows.

Early models for particle deposition were based on the stopping distance concept. According to this model, when particles reach their stopping distance, they are transported to the wall by the so-called free flight mechanism. Cleaver and Yates (1975) reported large discrepancies of the free flight model predictions with the experimental data for turbulent flow regimes.

In the last decade, the Direct Numerical Simulation (DNS) of Navier–Stokes equations provided a powerful tool for studying particle dispersion and deposition in turbulent flows at moderate Reynolds numbers. One-way coupled DNS of fluid flow with a Lagrangian particle tracking has been used to obtain detailed information on particle wall interactions for turbulent duct flows. McLaughlin (1989), Brooke et al. (1992), Squires and Eaton (1991), Soltani and Ahmadi (1995, 2000) and Soltani et al. (1998) used DNS to study particle deposition rate in turbulent channel flows. Although, DNS provides an accurate description of particle laden flows, it is restricted to low to moderate Reynolds numbers and simple geometry ducts. Some of the recent studies for the fiber deposition in complex respiratory passages were performed for laminar flows (Dastan et al. 2014). Recently, Tian and Ahmadi (2013) reported fiber transport and deposition in the upper airways using the Reynolds stress transport model. DNS or fiber transport and deposition in turbulent duct flows were reported by Zhang et al. (2001, 2007), and Soltani et al. (2000).

The presented literature survey shows that most of the earlier studies were concerned with the dispersion analysis of spherical particles. For non-spherical particles, earlier studies were reported for laminar shear flows, and there is only limited number of studies regarding turbulent dispersion of non-spherical particles. The aim of the present study is to develop proper stochastic models for analyzing dispersion and deposition of ellipsoidal particles in isotropic-homogeneous and inhomogeneous turbulent flows. In the following sections, first the mathematical background of the fiber motion is described. This is followed by the discussion of the method to incorporate the effects of turbulence fluctuations on fiber dispersion. Finally, performance of the developed model for dispersion of fibers in various turbulent flows are evaluated and discussed.

2. Mathematical background

2.1. Creeping flow formulation for fiber motion

The motion of a non-spherical particle is described using translational and rotational equations of motion. Translational motion is described using the equations of balance of linear momentum for the particles. Rotational motion is described by the equations of balance of angular momentum. To evaluate the motion of an ellipsoidal fiber, three Cartesian coordinate systems should be defined as shown in Fig. 1. The (x, y, z) coordinate system is the inertial coordinate system, while (x', y', z') coordinate system is the particle frame with the origin located at the fiber center of mass with the z' along the major axis of the fiber. The third coordinate system (x'', y'', z'') is the fiber co-moving frame with its origin at the particle centroid and its axes parallel to the inertial coordinate system. The inertial coordinate system is used to describe translational equations of motion while the rotational equations of motion are considered in the particle frame. The transformation from one to other coordinate system can be performed by means of the Euler angles φ, θ, ψ.

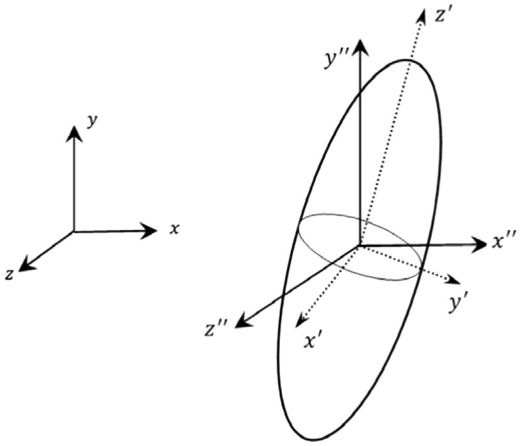

Fig. 1. Three coordinate systems for description of a fiber motion.