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A new model for the simulation of particle resuspension by turbulent flows based on a stochastic description of wall roughness and adhesion forces

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Abstract

We propose in this paper a new model aiming at simulating particle reentrainment in turbulent flows using stochastic Lagrangian methods. The resuspension model presented here emphasizes the role played by surface roughness in the reentrainment process, both in the stochastic calculation of adhesion forces based on a random model of large-scale and fine-scale wall asperities and in a newly proposed kinetic scenario of resuspension. The whole model has been implemented in a dedicated code and statistics of interest are obtained through Monte Carlo simulations. A step-by-step validation process is carried out by first assessing the adhesion-force sub-model, before analyzing the ability of the model to predict particle onset along the wall as measured in recent experimental studies. The complete particle resuspension model is then validated by comparing numerical outcomes to experimental data, where it is seen that the model is able to capture the various phenomena quite well. The present work follows a precedent study devoted to the modeling of particle deposition [Guingo, M., & Minier, J.-P. (2007). A stochastic model of coherent structures in boundary layers for the simulation of particle deposition in turbulent flows. In: *Proceedings of the 6th international conference on multiphase flow*. Leipzig, Germany; Guingo, M., & Minier, J.-P. (2008). A stochastic model of coherent structures for particle deposition in turbulent flows. *Physics of Fluids* 20, 053303].

Keywords: Particle resuspension; Reentrainment; Surface roughness; Stochastic model

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1. Introduction

Particle resuspension (also called particle reentrainment) refers to the process that leads to the separation between initially deposited particles and a wall. It occurs in many industrial processes involving dispersed two-phase turbulent flows and its prediction is of critical interest, for instance in the case of atmospheric pollution or of fouling of heat transfer surfaces in nuclear power plants. However, it is a very difficult issue to address because it covers fundamentally a wide range of complex and random sub-phenomena which, themselves, depend on several parameters. These sub-phenomena include near-wall turbulence, physico-chemical forces between particles and walls (electrostatic, van der

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Waals forces, chemical bonds) as well as particle and wall material characteristics (roughness, elasticity, deformation, particle size, etc.).

Over the years, several studies have been devoted to the identification of mechanisms responsible for particle resuspension and to the construction of theoretical models based on these mechanisms. These models have been divided in two categories in the comprehensive review of Ziskind, Fichman, and Gutfinger (1995). On the one hand, a class of models estimates particle resuspension rate by measuring the balance between hydrodynamic efforts and particle–wall adhesion bonds (Cleaver & Yates, 1973; Reeks & Hall, 2001) (the so-called "quasi-static" or "force-and moment- balance models"). On the other hand, a second class of models is based on finding conditions for a resonance in the particle–wall system that could lead to the breaking of adhesion bonds (Reeks, Reed, & Hall, 1988; Ziskind, Fichman, & Gutfinger, 2000), and is sometimes called "energetic" or "energy-balance models". Besides, near-wall coherent structures such as "bursts" have also been proposed to explain resuspension process. According to some research teams (Braaten, Paw, & Shaw, 1990), these violent and periodic ejections of fluid from the wall toward the core flow could directly remove particles from the wall surface.

Experimental programs have also been carried out in the past decades, mainly to measure the flow velocity necessary to bring about particle resuspension with respect to several parameters (particle diameter, material properties, etc.). Among recent works, we can cite the STORM program (Hontañón, de los Reyes, & Capitão, 2000), the experimental study of Reeks and Hall (2001) and the experiments of Ibrahim, Dunn, and Brach (2003) where special care has been taken to control critical parameters. Indeed, in particle resuspension studies, the main issue, when trying to obtain reliable experimental results, seems to be the number of factors to control at the same time so as to ensure an acceptable repeatability between trials.

In this paper, we propose a new stochastic Lagrangian model to simulate particle reentrainment based on a scenario that stresses the role of surface roughness, which aims at being implemented in a full Lagrangian approach to model particulate flows (Guingo & Minier, 2007, 2008; Minier & Peirano, 2001). It may be worth underlining that the objective is not to come up with a very detailed model limited to specific surfaces (whose surface roughness is known beforehand to be in a given range) but rather to develop a general model that can be applied for various surfaces. The paper is organised as follows: first, the resuspension scenario and the modeling issues are exposed. Then, the stochastic description of wall roughness is presented in Section 4 as well as the resulting model retained for adhesion forces. The hydrodynamic forces responsible for possible particle motion along the wall are developed in Section 5 while the complete resuspension model is put together in Section 6. The model has then been numerically implemented and a progressive validation methodology has been followed, starting from the most basic component (the adhesion submodel) up to the whole resuspension model, as presented in Section 7.4. As a first step, calculations of adhesion forces are compared to available experimental data. Then, we assess numerical results against the recent experimental study of Ibrahim et al. (2003) that focuses on the flow velocity level that causes particle to start moving on the wall. Finally, particle resuspension itself is studied by comparing our numerical results to different reentrainment experiments.

2. Overview of the proposed resuspension scenario

Due to the generally high intensity of adhesion forces and to the weakness of wall-normal hydrodynamic efforts in the immediate vicinity of the wall, direct pull-off (or direct removal) by wall-normal hydrodynamic forces is hardly probable (Ziskind et al., 1995). Consequently, other processes have to be at play and thus have been investigated. For modeling purposes, two main conclusions can be drawn from the existing literature:

- Recent experimental evidence (Ibrahim et al., 2003) tends to show that rolling or sliding motion on the wall are generally the main mechanisms that cause particle resuspension.
- Surface roughness plays an important role in the reentrainment process, by reducing the adhesion forces (Greenwood & Williamson, 1966) and because of the particular geometry of particle/asperity contact (Ziskind, Fichman, & Gutfinger, 1997).

Existing models such as the Rock'n Roll model of Reeks and Hall (2001) or the model of Ziskind et al. (1997) regard particles as being reentrained once there are set in motion by hydrodynamic efforts. Nevertheless, to our knowledge, particles which are set in motion may simply roll on the wall, thus avoiding an actual separation from the surface. Therefore, we propose here another scenario based on a two-step mechanism: first, due to longitudinal hydrodynamical