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Colloidal particle resuspension: On the need for refined characterisation of surface roughness

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ABSTRACT

This paper highlights the role played by surface roughness on the resuspension of nano- and micro-sized particles and, in particular, the need to extract more information from measurements of the surface profile than typical values such as the average roughness R_a and the rms roughness R_{rms} (usually obtained through AFM or SEM measures). For that purpose, standard experimental measurements of surface roughness are analysed. Then, numerical results obtained with a stochastic model for particle resuspension are analysed and compared to experimental data. This analysis reveals that particle resuspension can only be properly captured with more detailed representations of surface roughness that include information on the distribution of the curvature radius and surface coverage of roughness features.

1. Introduction

1.1. Particle resuspension phenomena

Particle resuspension is the process whereby particles deposited on a surface are detached from it and re-entrained into the fluid flow. It is an ubiquitous phenomena which has been studied extensively over the last decades. As emphasised in recent reviews (Boor, Siegel, & Novoselac, 2013; Gradoń, 2009; Henry & Minier, 2014a; Ziskind, 2006), it has received renewed attention over recent years due to its role in various environments, for example in sediment dynamics (Coleman & Nikora, 2008), for the issue of the re-entrainment of hazardous materials such as radioactive particles in nuclear power plant accidents (Stempniewicz & Komen, 2010) or in the context of walking-induced resuspension of airborne particles in hospitals (Kubota & Higushi, 2013).

One of the main challenges related to particle resuspension comes from its multidisciplinary aspects, which involves the coupling between fluid dynamics (particle-fluid interactions), interface chemistry (particle-surface adhesion forces) and material physics (surface roughness). Indeed, particle resuspension results from the competition between two opposite forces/torques: on the one hand, hydrodynamical forces that tend to pull or drag particles along the wall and, on the other hand, adhesion forces that tend to maintain these deposited particles on the wall (Barth, Preuß, Müller, & Hampel, 2014; Jiang, Matsusaka, Masuda, & Qian, 2008; Kobayakawa, Kiriyama, Yasuda, & Matsusaka, 2015).

Hydrodynamical effects comprise lift and drag forces which play a different role depending on the mechanisms at play in particle dynamics. It is however important to note that these hydrodynamical forces are relatively well understood. Consequently, what is mostly at stake in particle resuspension modelling is to capture the distribution of adhesion forces. These forces result from the

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interaction between surfaces and thus depend on a number of factors including those related to the nature of the surfaces in contact and to their geometrical characteristics (such as surface roughness). At this point, it is worth mentioning that adhesion forces differs if single particles are deposited on a rough substrate or if particles form multilayered deposits. The resuspension of multilayered deposits adds indeed further complexity since adhesion/cohesion forces depend on the morphology of the deposit formed. In the present article, we focus on single particles resuspended from rough surfaces and the case of multilayered resuspension is left out for future studies. For single particles attached to the surface, several recent measurements of surface forces have shown that adhesion forces are significantly affected by the irregular nature of surfaces (Audry, Ramos, & Charlaix, 2009; George & Goddard, 2006; Götzinger & Peukert, 2004; Prokopovich & Perni, 2010; Rabinovich, Adler, Ata, Singh, & Moudgil, 2000; Yang, Zhang, & Hsu, 2007; Zhou & Peukert, 2008; Zhou, Götzinger, & Peukert, 2003). These random variations of surface features met by deposited particles imply that adhesion forces can take a range of values and that the corresponding distribution needs to be characterised statistically either through its CDF (Cumulative Distribution Function) or its PDF (Probability Density Function).

One of the key challenge in particle resuspension is that it spans over a very long time-scale. In the context of radioactive or noxious particles, resuspension is usually decomposed in two parts (see for instance (Braaten, 1994; Hall & Reed, 1989; Reeks & Hall, 2001)): an initial short-term resuspension and a long-term resuspension. Short-term resuspension is characterised by the removal of particles that are weakly bounded to the surface, i.e. with small adhesion forces, whereas long-term resuspension involves the removal of particles that strongly adhere to the surface. The different behaviours between short-term and long-term resuspension rates is thus a direct consequence of the broad distribution in adhesion forces and, to a lesser extent, in hydrodynamic forces. As a result, when trying to ensure that the fraction of resuspended particles remains always below a given threshold value as in the case of nuclear safety (e.g. in Braaten, 1994; Wagenpfeil, Paretzke, Peres, & Tschiersch, 1999), detailed characterisations of the distribution of adhesion forces must be available. In particular, this includes information not only on the first few moments but also on the tails of these distributions (where extreme events occur).

1.2. Purpose of the paper

Drawing on these arguments, we have developed a model for particle resuspension that includes fine calculations of the adhesion forces between particles and rough surfaces (see Henry, Minier, & Lefèvre, 2012). This allows us to obtain the distribution of adhesion forces as an outcome of the modelling approach. The present approach can thus provide refined information for more macroscopic models, such as classical kinetic models (where the adhesion force distribution is an input Reeks & Hall, 2001), as well as to design new empirical formulae for the resuspension rate/adhesion force distribution that remain valid for a wide range of cases. This is further motivated by the fact that previous numerical results have been shown to compare well with experimental data on adhesion force and to reproduce various forms of the adhesion force distribution (including two-peaks, Gaussian or log-normal distributions) (Henry et al., 2012). Besides, this model for particle resuspension also allows us to extract the time-dependence of the resuspension rate that includes the effects of surface roughness. It has also been compared to existing experimental data on resuspension in previous papers (Guingo & Minier, 2008; Henry & Minier, 2014b; Henry et al., 2012). Such information will help to design and check the validity of empirical formulas for the resuspension rate which are source terms in some models for indoor resuspension (Kim, Gidwani, Wyslouzil, & Sohn, 2010).

Yet, one of the key difficulties encountered when assessing the model lies in the fact the amount of information on the topography of surfaces used in resuspension experiments is limited. In a recent paper, Barth et al. (2014) measured the resuspension of colloidal particles from rough substrates in a turbulent channel airflow at various friction velocities. These measurements provide not only information on the short-term resuspension (here after a 60 s exposure to a flow) but also on the roughness characteristics of the substrate. More precisely, surface roughness is quantified through a number of statistical numbers, such as the well-know R_a value or similar quantities. It remains to be seen whether this is sufficient for particle resuspension studies.

The aim of the present paper is thus to investigate whether current characterisations of surface roughness are adequate to fully capture particle resuspension using the recent measurements of Barth et al. (2014) for short-term resuspension. In that sense, the objectives of this paper are three-fold:

- to illustrate how surface roughness affects particle resuspension;
- to highlight the limitations of the experimental characterisations of surface roughness;
- to identify and underline the refined statistical descriptions required.

For that purpose, the recent dynamic approach for particle resuspension is briefly recalled in Section 2. Then, existing experimental data on the characterisation of surface roughness are analysed in Section 3. To highlight the need for more detailed characterisations of surface roughness, numerical results obtained with the modelling approach are compared to recent experimental data in Section 4. These numerical results are then used to suggest a refined characterisation of surface roughness in Section 5.

2. Present modelling approach

2.1. Existing models for particle resuspension

Various modelling approaches have been developed in the literature. Since this article is focussed on assessing the role of surface roughness in particle resuspension and the limitations of the current measurements, only the key features of existing models are