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A comparative study and a mechanistic picture of resuspension of large particles from rough and smooth surfaces in vortex-like fluid flows

Ron Shnapp, Alex Liberzon *

Tel Aviv University, School of Mechanical Engineering, Turbulence Structure Laboratory, Tel Aviv University, Tel Aviv 69978, Israel

HIGHLIGHTS

- Detailed three-dimensional measurements of freely moving large spherical particles over smooth and rough surface.
- Resuspension efficiency of the particles is higher above the rough surface due to reduced mobility.
- Total, kinetic and potential energy of particles above rough surface are all higher than the smooth case.
- Mechanistic picture explains the way the reduced mobility of the particles on the rough surfaces affects the resuspension efficiency.

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ABSTRACT

Resuspension of freely moving solid particles by a vortex-like flow from surfaces of different roughness is studied using a three-dimensional particle tracking velocimetry (3D-PTV) method. By utilizing the three-dimensional information on particle positions, velocities and accelerations before, during and after the lift-off events, we demonstrate that the resuspension efficiency of the larger than the roughness spherical particles is significantly higher from the rough surface as compared to the smooth surface. The results indicate that for all Reynolds numbers tested, the resuspension rate, as well as the particle velocities and accelerations, is higher over the rough surface, as compared to the smooth counterpart. A mechanistic picture that explains this peculiar effect is proposed. The results can help us to analyze the resuspension rates in engineering and environmental applications of similar flow cases and to improve the specific type of dynamic resuspension models.

1. Introduction

Particle resuspension is the process in which a submerged particle is being detached from a surface to the fluid medium above, after the break-up of the particle–surface bond. Resuspension is an ubiquitous process in many engineering and environmental applications, for instance in sediment transport (Wu and Chou, 2013), powder handling processes (Grzybowski and Gradon, 2007), and studies of Martian dust devils (Greeley et al., 2004). In Henry and Minier (2014) it was proposed to distinguish between two typical situations where the mechanisms of resuspension are different: for small particles, smaller than the viscous sublayer thickness, resuspension is governed by rolling/sliding motion with little direct effects of fluid structures (such as sweeps and ejections) and a stronger importance for the interplay between adhesion and hydrodynamic forces and surface roughness; while for large particles, larger than the viscous sublayer thickness, resuspension is markedly influenced by fluid flow events such as sweeps and ejections and with direct particle lift-off resuspension phenomenon occurring. The dependency of the resuspension phenomena on diverse flow regimes makes it hard to study in a general fashion. Therefore, we believe that the detailed study of resuspension will benefit from a break-up of the mechanism as a whole into separate stages, so in the future, the broad picture may be better understood. In this work we want to focus on the stage of the freely moving particle lift-off from smooth or rough surfaces. The size of the particles is larger than the sublayer thickness and then roughness asperities and therefore fall to the second category as classified in Henry and Minier (2014). The present study complements the previous studies by considering the effect of particle motion along the wall. This type of problems relates to the so-called dynamical models, as distinguished from classic resuspension models which are static models and the resuspension is identified with the disrupted particle equilibrium on a wall, see Henry and Minier (2014).

* Corresponding author.

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Recent reviews of particle resuspension from surfaces by Ziskind (2006), Henry and Minier (2014) emphasized that the complexity of the resuspension phenomena is caused by two inherent features: particle interaction with the surface to which it is attached, and particle interaction with the fluid to which it is exposed. On rough walls the particle–surface interaction depends on the size and shape of asperities relative to the size of the particle. In addition, above a certain Reynolds number, the boundary layer flow changes and so the particle–fluid interaction mechanisms. It is also possible that there is a fluid filled asperities that react differently to the fluctuations of hydrostatic pressure. Therefore, it is should not be surprising that studies have shown various (often opposite) trends of the resuspension process efficiency caused by subtle changes of the wall surface roughness or particle diameter (e.g. Nino et al., 2003; Yanbin et al., 2008; Lee and Balachandar, 2012; Barth et al., 2014, among others).

Surface roughness can have different effects on the resuspension rate depending on different mechanisms. For instance, Henry et al. (2012) in their model of re-entrainment coupled surface roughness with the effect of particle–surface adhesion. Lee and Balachandar (2012) calculated a critical shear stress criterion for the initiation of particle movement, and determined that surface roughness may affect particle movement through the level of relative particle protrusion, or through a moment balance of hydrodynamical and resistive forces against an asperity. Using a channel airflow experiment, Yanbin et al. (2008) demonstrated that the effect surface roughness has on resuspension varies for particles of different sizes and for different scales of surface roughness. Hall (1988) measured and derived an expression for the lift force acting on a particle on smooth and rough surfaces, and found that the force can change by several orders of magnitude depending on the surface roughness, and depending on the position of a particle relative to the roughness elements. Because of the variety of mechanisms related to the surface roughness, in this study we choose to focus on a single aspect of this diverse phenomenon, namely on the way by which particle mobility over the smooth and rough surfaces (the ability to roll or slide along the surface) affects resuspension of relatively large spherical particles. We consider the spherical particles of diameter d_p larger than the roughness average height, R_a and larger than the thickness of the viscous sublayer, i.e. $R_a/d_p \ll 1$, $d_p^+ \approx 30$.

Many experimental methods have been introduced so far for measuring resuspension rates. The majority of studies were conducted through a wind tunnel or a duct flow with particles spread over the channel bed. The initial load of particles is measured and particles that leave the observation volume are counted, providing the fraction remaining (Ibrahim and Dunn, 2003; Nino et al., 2003; Yanbin et al., 2008, among others). Other experimental methods intended to study resuspension under specific flows, such as the air flow generated by the foot during walking, or through porous medium, have also been introduced – examples can be found in a recent review by Henry and Minier (2014). These methods allow to quantify the resuspension rates and test models of the resuspension problem at large. For our purpose of studying the basics of the resuspension mechanism, and focusing on a single major difference between the smooth and rough surfaces, an experiment with a confined flow and particle motion, along with the detailed three-dimensional measurements, is required.

In order to achieve a quasi-static state, a steady vortex flow type was chosen. On one hand this flow case mimics several industrial applications such as magnetic mixers (Halasz et al., 2007), bio-reactors (Lavezzo et al., 2009), settling tanks (Baud and Hager, 2000) and natural flows like tornadoes or dust devils (Balme and Hagermann, 2006; Greeley et al., 2003, 2004), and on the other hand it resembles the funnel vortices observed in wall bounded open channel flows, Kaftori et al. (1994). The low pressure, found at the center of a vortex-like swirling flow, creates a “suction” effect that generates high lift forces over submerged bodies. As a result, vortex flows present higher resuspension rates at a low level of energy input to the system, as compared to the unidirectional boundary layer type of flows. Moreover, the low pressure zone at the vortex core keeps the initial group of particles within a observation volume, thus allowing high fidelity measurements and significant statistics based on long and detailed observations to be collected for relatively small groups of test particles. Using a three-dimensional particle tracking velocimetry (3D-PTV) system, the particle locations, velocities and accelerations can be measured in time, and thus different aspects of their instantaneous and statistical behavior can be put under examination (e.g. Traugott et al., 2011).

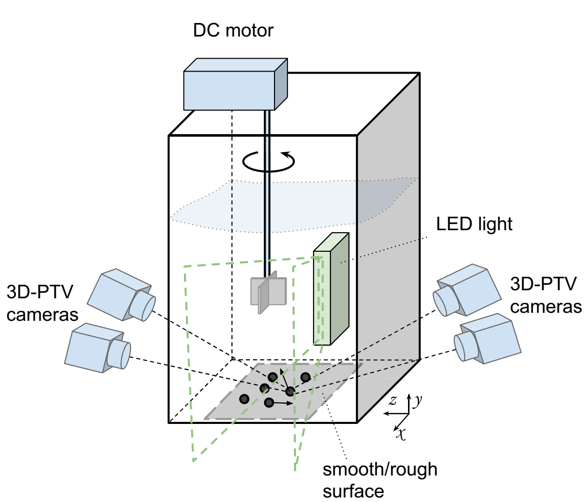

Fig. 1. Schematic view of the experimental set up: water tank, four-blade rotor, overhead stirrer driven by a DC motor, replaceable smooth or rough surfaces with the freely moving particles, four high speed digital cameras and LED line light source. The coordinate system is defined with the vertical y-axis.

2. Materials and methods

2.1. Experimental methods

The experimental set up is shown in Fig. 1. A $300 \times 300 \times 400\ \text{mm}^3$ glass tank is filled with filter water at room temperature (density $\rho = 1000\ \text{kg m}^{-3}$ and kinematic viscosity $\nu = 10^{-6}\ \text{m}^2\ \text{s}^{-1}$) up to 230 mm height. A four blade rotor rotates on a shaft of a stirrer equipped with an angular velocity control (RD-03, MRC Inc.). At the tank bottom wall, the different roughness surface can be attached. Four high speed digital CMOS cameras were placed around the tank, along with two LED lights. The digital video data was recorded to the RAM of a video recording unit and processed later using an open source particle tracking velocimetry software, OpenPTV (OpenPTV consortium, 2013). We tested four different angular velocities of 70, 100, 130 and 160 rpm and the bulk Reynolds number of this vortex type of flow is defined using the stirrer radius R, and the motor angular velocity ω, $Re = \omega R^2/\nu$. The corresponding Reynolds numbers tested are in the range of 1.3×10^4 to 3×10^4. Each experiment was repeated at the steady state conditions, after the motor was running for at least five minutes with the particles in the tank, so the flow was allowed to reach a stable steady state vortex flow. After establishing the steady flow and resuspension conditions, a digital video sequence from different view angles was taken at a rate of 500 frames per second with the cameras focused at the