ON RESUSPENSION OF SPHERICAL PARTICLES FROM ROUGH AND SMOOTH SURFACES BY A WALL-NORMAL VORTEX

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Abstract A three-dimensional particle tracking velocimetry (3D-PTV) method was applied to study in details the single-particle resuspension (lift-off) events of large spherical particles. In order to increase statistics, we have utilized a wall-normal, tornado-like vortex that lifted the particles from surfaces of different roughness. Analyzing the three-dimensional particle trajectories, velocities and accelerations before, during and after the resuspension events, the resuspension efficiency was obtained directly. The results show that the lift-off efficiency from the rough surface is significantly higher than from the smooth one. We suggest a simplified mechanistic model based on the mobility parameter that can predict this peculiar effect. This study can lead to improved modeling of resuspension rates from smooth and rough beds.

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 [1], powder handling processes [2], and studies of Martian dust devils [3]. In our view, the detailed study of resuspension demands 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.

Surface roughness can be seen to effect resuspension rates in many different ways. Two examples are, Henry et al. (2012) [4] who coupled surface roughness with the effect of particle-surface adhesion, or Lee & Balachandar (2012) [5] that 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. Examples can also be given for studies that showed different behaviors of particles related to the scales of the problem. To name two - Yanbin et al. (2008) [6] demonstrated that the effect surface roughness has on resuspension varies for particles of different sizes and for different scales of surface roughness, and Hall (1988) [7] that 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 with surface roughness, and with the position of a particle relative to the roughness elements. In our study, we choose to focus on a single aspect of this diverse phenomena, namely on the way by which particle mobility (rolling or sliding motion along the surface) over the smooth and rough surfaces affects resuspension of relatively large spherical particles.

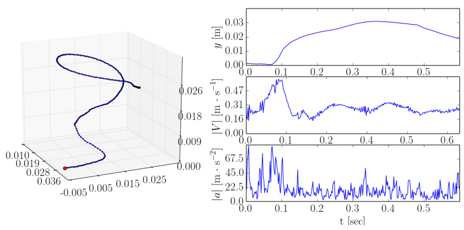

Figure 1. (left) isometric view of a single particle trajectory experiencing the resuspension event, (right) - the height above the surface (top), the velocity (center) and acceleration (bottom) magnitude of the particle in time.

EXPERIMENTAL INVESTIGATION

For our purpose of studying the basics of the resuspension mechanism, focusing on a single major difference between the smooth and rough surfaces, an experiment with a confined flow and particle motion, along with detailed three-dimensional measurements, are required. In order to achieve a quasi-static state, a steady vortex flow type was chosen. 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 particles' locations and velocities can be measured in time, and thus different aspects of their instantaneous and statistical behavior can be put under examination.

Our measurements were taken using soda lime glass spherical particles $d_p = 800\,\mu$m in diameter, a "smooth" - $Ra = 0.65\,\mu$m surface, and a "rough" - $Ra = 14.24\,\mu$m surface. Once the Lagrangian positions of the particles were determined in time and their velocities and acceleration were calculated (see figure 1) the analyses of the results focused mainly on the statistical behavior of the kinematics and the dynamics of the continuously resuspending particles inside the vortex core. Thus, distributions of kinetic and potential energies, particle accelerations and particle entrainment rate were plotted for the different runs of the experiment. The results of our analyses indicate that throughout the range of measurements made, particle above the rough surface tend to posses higher values of each of the properties stated above, as higher probabilities were witnessed for the mechanical energy, for the accelerations and for the resuspension rates.

DISCUSSION

The results presented in our work show unequivocally that in the case of spherical particles with a diameter larger than the viscous sublayer, roughness improves the resuspension rates. It is important to note that this result is new both at the level of the detailed information about trajectories of the freely moving particles as they are suspended or deposited, and at the direct comparative study of the smooth versus rough surfaces under the same flow conditions. This experiment allows us to single out the mechanism by which the resuspension rate increases for the mobile beds over the rough surfaces.

To conclude, we propose a simplified conceptual mechanistic model that explains the differences of the spherical particles resuspension from the two surfaces. The model is relevant only for particles large enough, such that the adhesion to the smooth surface is negligible, as compared to hydrodynamic forces. In this case, as can be seen in 2, the spherical particle on a smooth surface can roll or slide, whereas on a rough surface this ability is impaired. The major difference and the increased resuspension rate over the rough surface is therefore due to the strongly increased relative velocity between the particle and the flow, i.e. $W = U - V_p$. Since the major hydrodynamic forces of lift and drag are both proportional to some power of the relative velocity $L, D \propto W^\alpha$, which, depending on the particle Reynolds number, can be in the range of $\alpha = 1 \div 2$, the increase of the forces acting on a particle over a rough surface can be up to the W^2.

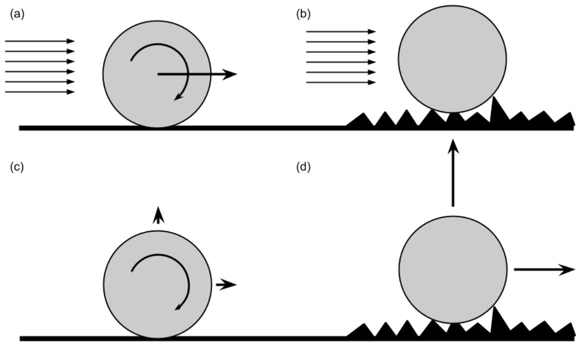

Figure 2. Cartoon of the large spherical particle resuspension from smooth (left panel) versus rough (right panel) surfaces: (a) spherical particle under the flow from the left can roll or slide at the velocity comparable to the flow velocity, (b) same particle on the rough surface cannot roll or slide due to the roughness, (c) the very small relative velocity of the particle decreases significantly the drag and lift forces responsible for the resuspension; (d) lift and drag forces are enhanced due to a very high relative velocity which in this model is equal to the flow velocity.

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