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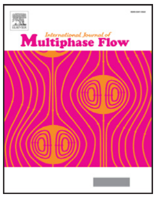

Experimental study of forces on freely moving spherical particles during resuspension into turbulent flow

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ABSTRACT

Turbulent resuspension, a process of lifting solid particles from the bottom by turbulent flow, is ubiquitous in environmental and industrial applications. The process is a sequence of events that starts with an incipient motion of the particle being dislodged from its place, continues as sliding or rolling on the surface, ending with the particle being detached from the surface and lifted up into the flow. We study the resuspension of solid spherical particles with the density comparable to that of the fluid, and the diameter comparable with the Kolmogorov length scale. Three-dimensional particle tracking velocimetry (3D-PTV) tracks particle motion during the lift-off events in an oscillating grid turbulent flow. We measure simultaneously the Lagrangian trajectories of both the particles freely moving along the bottom smooth wall and the surrounding flow tracers. Different force terms acting on particles were estimated based on particle motion and local flow parameters. The results show that: *i*) the lift force is dominant; *ii*) the drag force on freely moving particles is less relevant in this type of resuspension; *iii*) the Basset (history or viscous-unsteady) force is a non-negligible component and plays an important role before the lift-off event. Although we cannot estimate very accurately the magnitude of the force terms, we find that during the resuspension the dominant forces are $2-10$ times the buoyancy force magnitude. The findings cannot be extrapolated to particles, which are much smaller than the Kolmogorov length scale, or much denser than the fluid. Nevertheless, the present findings can assist in modeling of the sediment transport, particle filtration, pneumatic conveying and mixing in bio-reactors.

1. Introduction

Resuspension is the process of particle release from a surface into a surrounding fluid flow. In order to distinguish the entrainment into a flow from a motion along the surface (sliding or rolling), it is often denoted as “lift-off” (Brennen, 2005; Henry and Minier, 2014; van Rijn, 1984). Resuspension of particles is an important mechanism in a variety of practical applications, such as particle filtration (Huang et al., 2008), oil production (Middletich, 1981), contamination in clean rooms (Dixon, 2006), pneumatic conveying (Soepyan et al., 2016) and particle behavior in respiratory ways (Sarma et al., 1992). In order to predict particle resuspension accurately, the relation of the incipient motion and the removal of particles from surfaces to the particle/fluid properties and the local flow regime need to be understood in detail. Prediction of lift-off events in turbulent flows requires understanding of both the surrounding flow field and the particle-flow interaction. The latter is based on the balance of forces and moments resulting from stress applied on the particle by the local flow and the restrictive forces of gravity and surface/particle interactions (Henry and Minier, 2014; Ziskind, 2006).

Despite numerous experimental and numerical studies addressing the problem of incipient motion in general, and lift-off in particular, the question of which mechanism dominates the process remains open. Several studies propose that particle motion is predominantly driven by the magnitude of fluctuating drag and lift forces exerted on particles, depending on their degree of exposure to the flow (Dwivedi et al., 2011; Schmeeckle et al., 2007). The importance of instantaneous fluctuating velocities might indicate that the turbulence structure at the near bed is ultimately responsible for particle motion (McLean, 1994). Gimenez-Curto and Corniero (2009) suggested that the critical motion is related to the maximum forces acting on the particles, rather than the mean bed shear stress. Celik et al. (2010) found that the time duration of the force above a certain threshold is the critical parameter.

With respect to the direction of the force acting on particles fixed on the bottom, the discussion is divided between the drag force (a component parallel to the streamwise flow velocity) and the lift (perpendicular, vertical) force. For turbulent flows with the

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streamwise flow direction parallel to the bottom bed surface, the hydrodynamic drag term is considered to be dominant. For instance, Schmeeckle et al. (2007) used a force transducer directly connected to a particle to measure force synchronously with the flow velocity measurements above or in front of the particle. The horizontal force was shown to correlate with the magnitude of the downstream velocity, but not with the vertical velocity component. In this experiment, the standard drag model, based on the streamwise velocity, predicted the horizontal force acting on a fixed and fully exposed particle (Schmeeckle et al., 2007). The vertical force, on the contrary, correlated poorly with both horizontal and vertical velocity components. Similarly, Nelson et al. (1995) have reported strong correlation between sediment rate (number of resuspended particles) and streamwise velocity fluctuations near the bed, opposite to weak correlation with the fluctuations of vertical velocity. Mollinger and Nieuwstadt (1996) studied the lift force and could confirm experimentally the predictions of the mean lift force of Hall (1988). In a similar type of study, Dwivedi et al. (2011) used a force sensor attached to a fixed particle. The authors concluded that the lift force is produced primarily by the pressure gradient in the flow due to externally imposed unsteadiness of the flow or turbulent fluctuations. Dwivedi et al. (2011) suggested a particular local turbulent flow structure that could produce high pressure below the particle and low pressure above it, leading to high lift force. A similar mechanism was proposed by Zanke (2003) as a possible cause of particle suspension.

It is noteworthy that the aforementioned studies measured forces on fixed particles. Moreover, due to the resolution of force sensors, the particles were relatively large. There is no information on the forces applied by a turbulent flow on freely moving particles. Recently we have developed the necessary tools for such measurements. In Shnapp and Liberzon (2015), the trajectories of spherical particles lifted off smooth and rough surfaces were measured in a tornado-like vortex flow. Meller and Liberzon (2015) have extended the Sridhar and Katz (1995) method to measure the relative velocity between a particle and the surrounding turbulent flow, and estimate various components of force acting on suspended particles. Combining these two developments with the oscillating grid apparatus presented by Traugott et al. (2011), in this study we estimate the force components acting on particles freely moving on the bottom wall and the relative contributions of force components to the lift-off events.

We utilize the three-dimensional particle tracking velocimetry (3D-PTV) to obtain velocity and acceleration data along trajectories of tracers and large spherical particles, as described in Section 2. The method provides parameters of individual, freely moving solid particles before, during, and after the lift-off events. These measured simultaneously with the local turbulent flow, represented by Lagrangian tracer trajectories. We focus on the moment of lift-off of the particle from the wall and its relation to the local turbulent flow characteristics. Applying the particle equation of motion, we estimate the magnitude and direction of inertia, pressure, drag, lift and Basset force terms and their effect on the lift-off events. Experimental results are presented in Section 3 and discussed in the closing Section 4.

2. Methods and materials

2.1. Experimental setup

The oscillating grid setup is shown schematically in Fig. 1. The system comprises of a glass tank (30 × 30 cm and 50 cm tall) and a vertically oscillating grid on an eccentric shaft driven by a 1.5 kW variable speed electrical motor (CDF90L-4, Kaijieli Inc.). The tank was filled with filtered tap water until a height of 220 mm, the grid height was set within the range of $h = 100 - 101$ mm (measured from the bottom of the chamber) and stroke amplitude (peak-to-peak) $s_l = 10$ mm. The frequency of oscillation of the grid is controlled by changing the input voltage to the motor. We present here the results of the runs at 1.5, 1.7, 1.2 and 2.1 Hz . The grid, shown in a top view in Fig. 1 was made of square bars covered by a plastic sheet with a 4 × 4 arrangement of circular holes, in order to increase the grid solidity to 80%. Lower solidity grids did not create a sufficient number of particle lift-off events.

Prior to the 3D-PTV study, the flow field under the grid was characterized using particle image velocimetry (PIV), see Traugott et al. (2011). The PIV data allows to define the important scales of turbulent flow under the oscillating grid. The Kolmogorov length scales varied within the range $\eta = (\nu^3/\varepsilon)^{1/4} = 270 - 330\ \mu$m and the Kolmogorov time scales were estimated as $\tau_\eta = (\eta/\nu)^{1/2} = 0.07 - 0.1$ s. The flow under the grid was neither homogeneous nor isotropic, as it might be expected due to the relative proximity of the grid to the bottom wall and the large solidity.

The 3D-PTV experimental system, shown schematically in Fig. 1, included the following components: the digital video recording system (IO Industries Inc.) and four high speed CMOS cameras (8 bit, 1280 × 1024 pixels, EoSens GE, Mikrotron), equipped with 60 mm lenses (F-mount, Nikon). The cameras capture simultaneously (with a maximum possible time jitter of 0.001 fps) a digital video recorded at the rate up to 700 Mb/s on high-speed hard drives. The data is analyzed using the open source software, “OpenPTV” (OpenPTV consortium, 2013).

The cameras were located in an angular array from two sides of the grid chamber, as shown in Fig. 1. The four cameras arrangement reduces the number of ambiguities and allows reliable determination of most of the particles which are completely hidden in one of four images (Dracos, 1996). In the particular runs reported here, the image acquisition rate was set to 160 fps, the observation volume was 7.5 × 4 × 6 cm^3 (length × width × height). Two light emitting diodes (LED) line sources (Metaphase, USA) illuminated the observation volume in the center of the grid chamber. The combination of the two LED light sources provided a nearly uniform light intensity across a wider observation volume. A two step calibration method was used: a static calibration, using a three-dimensional reference target, and a dynamic calibration, using a dumbbell (wand) moving in a measurement volume after the grid was installed in the operating condition (OpenPTV consortium, 2013).

Two different types of particles were used in order to obtain simultaneous recordings of the turbulent flow and the motion of the inertial particles in the same observation volume. Polyamide particles with a mean diameter of 50 μm and density of 1030 kg/m^3 (Dantec Dynamics Inc.) were used as tracers. The relaxation time of flow tracers, $\tau_p = \rho_p d_p^2/18\mu$ is approximately 0.143 ms, which is significantly smaller than the Kolmogorov time scale of the flow and their Stokes number is small, $St < 0.01$. Furthermore, the particles fulfill the conservative restrictions for flows with acceleration of less than 10 m/s^2 e.g. Dracos (1996) (see class of neutrally buoyant, $d_p < 60$ μm particles), and therefore behave as tracers in a given turbulent flow.

Silica gel spheres (Fulka Inc.), 550 μ*m* in diameter (of the order of magnitude of the Kolmogorov length scale) and an effective density of $\rho_p = 1062$ kg/m^3 were used as the inertial particles. Their Stokes number is approximately equal to 0.2.

Before each experimental run, approximately 30 inertial particles were spread randomly on the bottom. Each run started in stagnant water, and after a certain time, the inertial particles were entrained into the water column by the turbulent flow generated under the constantly oscillating grid. For the chosen frequencies (1.5,1.7,1.9 and 2.1 Hz), all inertial particles became suspended. The number of particles spread on the bottom of the tank was relatively low and they were lifted-off separately, without