Resuspension of particles in an oscillating grid turbulent flow using PIV and 3D-PTV

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Abstract. Description of the mechanisms responsible for the initiation of particle motion from a surface and re-entrainment of particles into suspension remains a challenge, partially due to the technical difficulties to quantify the forces applied on the particles and the collection of high resolution data of particle displacements simultaneously. In this study we explore the process of initial entrainment of spherical particles from smooth beds into zero-mean-shear turbulent flow in an oscillating grid chamber. Particle image velocimetry (PIV) and three-dimensional particle tracking velocimetry (3D-PTV) are used to correlate in a quantitative manner the turbulent flow properties responsible for pick-up, detachment and re-entrainment of particles. The results are compared to the existing models of critical shear velocity and provide further insight into the resuspension process of spherical particles in the transitional range of particle size Reynolds numbers $2 \leq Re_p \leq 500$.

1. Introduction

Resuspension of particulate material exposed to a moving fluid is a common occurrence in nature (sediment transport) and an important mechanism in a variety of engineering applications, such as silicon wafer cleaning and pneumatic conveying. Despite a significant progress in the field of sediment transport during the past decades, the prediction of the flow conditions at which incipient motion occurs is still elusive. Thus, the processes of detachment of a particle from a surface and re-entrainment into suspension have not, until now, been fully clarified. This is partially related to the fact that only few experiments observed directly the motion of particles at the beginning and during the detachment (e.g. Ziskind, 2006, among others).

Different models have been proposed to define threshold flow conditions for the particle incipient motion using particle-turbulence interaction as the major mechanism of the phenomena (NiNo et al., 2003, and references therein). Following the experiments in which entrainment was observed to occur not as a completely random process, but rather as an intermittent process with groups of particles being suspended, several models that consider turbulent coherent structures have been proposed (Ziskind, 2006). The key role in such models play as coherent structures with large vertical velocity components, $v$, that exceed the particle settling velocity, $v_s$. Since in boundary layers velocity components are proportional to the friction velocity, $u_* = \sqrt{\tau_w/\rho}$ ($\tau_w = \mu \partial U/\partial y|_{y=0}$ is the mean wall shear stress), the critical conditions for the initiation of suspension (pick-up or lift-off) are defined in terms of friction...
velocity, i.e. $u_s/v_s \geq 1$. It is noteworthy that some works reported critical values to be much lower $u_s/v_s = 0.25 \div 0.85$ (NiNo et al., 2003, and references therein).

In flows without mean shear it is impossible to define the friction velocity in terms of the mean shear $\partial U/\partial y$, therefore another term to quantify the turbulence is required. It was proposed that root-mean-square of turbulent fluctuating velocity, $u'_{rms}$ characterizes the resuspension process Medina et al. (2001b); Orlins & Gulliver (2003); Belinsky et al. (2005, and the references therein).

Yet it is possible that another flow condition, such as Reynolds stress or anisotropy characteristics (the ratio of the vertical to horizontal velocity), govern the resuspension mechanism in the flow.

It was also observed that transients (i.e. unsteady flow phenomena) play a key role in particle detachment (e.g. Ibrahim & Dunn, 2006). Even in steady flow experiments, a higher entrainment rate is observed when the flow is initiated and it decreases with time as the flow is established. It is naturally expected that transients produce higher forces than the steady flows. Hence, in periodic unsteady flows, such as an oscillating grid turbulence, the transients are generated repeatedly.

This study explores the necessary conditions for initial entrainment of spherical particles from smooth beds into zero-mean-shear turbulent flow in an oscillating grid chamber, in a similar manner to the studies of (Medina et al., 2001a; Redondo, 2001; Liu et al., 2004) The experiments are not designed to fully mimic the real problem of sediment transport, but rather identify key mechanisms, utilizing direct observation and quantification of particle motion at the beginning, during and after lift-off.

Particle image velocimetry (PIV) was used to determine the properties of turbulent flows, and three-dimensional particle tracking velocimetry (3D-PTV) was used to track the movement of individual particles through the various phases of the resuspension. The combination of the experimental methods allows correlation in a quantitative manner the flow conditions responsible for pick-up, detachment and re-entrainment of particles.

The paper is organized as follows. Section 2 describes the methods of research, namely the oscillating grid facility and the PIV/PTV measurement systems. Section 3 is devoted to the results, followed by discussions and conclusions in Section 4.

2. Experimental methods

The experimental setup contains a tank made of glass (square cross-section 0.3 × 0.3 m, 0.5 m tall) in which a grid of square bars (grid solidity was adjusted to 0.63 using a plastic sheet with circular holes) oscillates vertically, driven by a 1.5kW variable speed electrical motor and an eccentric. The grid moves with 10 mm peak-to-peak amplitude and a frequency of up to 20 Hz. In the present experiment the grid was set to move within the range of $h = 52 \div 62$ mm, measured from the bottom of the tank.

Velocity measurements were conducted using a high-resolution CCD camera (4008 × 2672 pixels, 12 bit) and dual-head Nd:YAG laser (NewWave Solo 120 mJ/pulse, 532 nm) as shown schematically in Figure 1(a). Polystyrene seeding particles (11μm mean diameter) served as tracers in water. Data was recorded using Insight 3G software and analysed using open source PIV software (www.openpiv.net) for four different oscillating frequencies of the grid : 1.3, 1.7, 2.0 and 2.5 Hz. This range was found to span from the minimum frequency required to suspend few particles to the frequency at which all particles became suspended.

The 3D-PTV setup consists of four digital CMOS cameras (1280×1024 pixels, 8bit, Mikrotron GmbH). The cameras simultaneously captured (maximum possible time jitter of 1/1000 frame rate) and stored the digital video at the maximum rate of 700 Mb/sec using a digital video recording system consisting of 48 drives and four CameraLink Full frame grabbers (CLFC, IOI). The system is installed with the 3D-PTV open source software (ptv.origo.ethz.ch). The cameras were located in an angular array from two sides of the grid chamber, symmetric as
Figure 1. Experimental setup (a) PIV setup, (b) 3D-PTV setup

much as possible to each other, as shown in Figure 1(b). Green (530 nm) LED line light source (Metahpase, USA), illuminated the observation volume of interest in the center of the cavity. Solid particles were randomly distributed at the bottom of the grid chamber. All the runs started in still liquid and after a certain time of the grid oscillatory motion, the particles were entrained into the water column by the flow generated by the constantly oscillating grid.

In the 3D-PTV method, the pixel position of the particles in four image planes are translated into 3D physical coordinates \((x, y, z)\) based on the calibration of the imaging system. An accurate calibration of the system (determination of camera exterior and interior orientations, lens distortion and further disturbances) is important in order to get the exact complex geometric modelling which is affected by three optical media with different refractive indices. In our 3D-PTV experiments, we used the two step calibration method: i) using a static 3D body with accurately marked dots at given positions, and ii) the so-called “dumbbell calibration”, using a dumbbell shaped target (two beads 4 mm in diameter spaced 23 mm apart). For static calibration, a single image per camera is sufficient to solve the calibration problem approximately. During the second stage, several hundreds of dumbbell images were taken from each camera with the dumbbell in different positions within the field of view in order to improve the calibration to the necessary level of accuracy.

**Particles** Silica gel (Fulka Inc.) particles were used in this study with the mean diameter of 700 \(\mu\)m. A standard settling test was applied to measure the settling (terminal) velocity of the particles and to determine their effective density \(\rho \approx 1700 \text{ kg/m}^3\). The spherical shape of the particles was verified under the microscope. For the sake of comparison, with the existing resuspension models we estimate the Shields parameter using the method of Madsen & Grant (1976). The authors modified Shields diagram into the diagram showing the relation between the critical Shields parameter \(\theta_c\) and the so-called sediment-fluid parameter:

\[
S_* = \frac{d \sqrt{(s - 1)gd}}{4\nu}
\]

In our case, the sediment-fluid parameter is estimated as \(S_* \approx 12\). According to the Shields diagram, the selected particles-fluid combination corresponds to the lowest possible critical value of \(\theta_{cr} \approx 0.035\). The critical velocity \(u_{cr}\) is therefore estimated as 0.01 m/s and the respective
Figure 2. Typical sequence of events registered as pick-up or resuspension event. Time interval between the frames (a) - (f) is approximately 0.5 seconds.

The critical shear stress is:

\[ \tau_{b,cr} = \rho u_{scr}^2 = 0.1 \, N/m^2 \]

It is noteworthy that the lowest possible critical value of \( \theta_{cr} \) corresponds to the transitional turbulent flow, i.e. range of \( 2 < Re < 500 \) (particle size Reynolds number).

Four series of resuspension experiments were conducted corresponding to the four oscillating frequencies (1.3, 1.7, 2.0 and 2.5 Hz, respectively). For each oscillating frequency, three experiments in different water depth (13, 16 and 18 cm) were conducted. Two additional 3D-PTV measurement tests with PIV seeding particles only (11 \( \mu \)m diameter polystyrene particles), were made in order to verify the velocities obtained from the PIV measurements.

3. Results and discussion

This section is devoted to the presentation of the experimental results. The results are divided into three groups - i) the results obtained using manual analysis of digital video recordings, ii) the results of the PIV experiments, and iii) the 3D-PTV results.

3.1. Visualization results

Resuspension events were recorded using the 3D-PTV system at various frequencies. The objective of the first set of the experiments was to define experimental conditions for the following PIV and 3D-PTV runs. During the first set the resuspension events were noted and manually analyzed. For the conditions of these experiments, particles resuspension occurred in different modes: sometimes rolling and/or sliding, followed by lift-off and some particles were detached immediately. It is noteworthy that detachment of the particle from the bottom surface was not necessarily followed by re-entrainment, some particles were deposited almost immediately. There are also particles that remained adherent to the bottom after rolling or sliding. Some particles were suspended in groups, especially in the higher frequencies (2.0 Hz and 2.5 Hz) while others were lifted off individually. The time of incipient motion (defined as movement on the surface before pick-up) was estimated in the order of a tenth of a sec. A typical sequence of events that is defined as resuspension or pick-up is shown in Figure 2.
In this section, resuspension is described as a fraction of resuspended particles versus frequency of the grid, the so-called “pick-up ratio”. This fraction is defined as:

\[ \eta(t) = 1 - \frac{n(t)}{n(0)} \]

where \( n(t) \) is the number of particles on the surface at time \( t \). Practically, in each video frame the number of particles was counted manually and the ratio was estimated using recordings of different cameras. In Figure 3 we present two results: (a) the first time instant \( t_i \) at which the resuspension initiated, i.e. \( \eta(t_i) < 1 \), and in (b) we present the result at large times, i.e. \( \eta(t \rightarrow \infty) \). There are clear trends in the results: the oscillating frequency of the grid initiates the resuspension events at shorter time and the total number of resuspended particles increases with the increasing frequency. We also tried to emphasize that the total depth of water in the tank (keeping the height of the grid above the bottom constant) plays some role but the results are not conclusive enough to draw a single conclusion. In general, we note that the experiments that define detachment or resuspension ratios need to be performed and compared at exactly the same conditions, some of which are not always available to the authors (e.g. total depth of water in the water channel stream).

3.2. PIV results
Figure 4(a) shows the mean velocity magnitude as a function of the frequency of oscillation, indicating a clear trend: the mean velocity increases with increasing the frequency. As was shown in Figure 3(b), the number of resuspended particles also increases with the increasing frequency. Therefore, we cannot exclude the possibility that the entrainment of particles into suspension is related not only to the turbulent, but also to the mean velocity under an oscillating grid.

In Figures 4(b)-(d) we present the r.m.s velocity, the turbulent intensity and the Reynolds shear stress, \(-\langle u'v' \rangle\), respectively. The velocity fluctuation is defined as \( \langle u'_i = u_i - U_i \rangle \), where \( u_i \) is the instant velocity and \( U_i \) is the mean velocity. The r.m.s. of the turbulence fluctuation was calculated from velocity fluctuation \( u_{rms} = \sqrt{\langle u'^2 + v'^2 \rangle} \). The turbulent intensity was obtained by dividing the r.m.s. velocity by the mean velocity magnitude \( \sqrt{u'^2 + v'^2} / \sqrt{U^2 + V^2} \).

Figure 4(b) presents an interesting trend: for frequencies 1.3 Hz and 1.7 Hz, the r.m.s. value increases with frequency, but at frequency of 2.0 Hz the r.m.s. value falls close to the value obtained for 1.3 Hz and then increases again for 2.5 Hz. Therefore, although we obtained more resuspension events for 2.0 Hz than in 1.3 Hz, their r.m.s. values are almost the same. The explanation to that could lie either in the flow characteristics or in the definition of r.m.s.
Figure 4. (a) Mean velocity magnitude, $\sqrt{U^2 + V^2}$ and turbulent flow properties: (b) root-mean-square of the fluctuating velocity $\sqrt{u'^2 + v'^2}$, (c) Turbulent intensity $\sqrt{u'^2 + v'^2} / \sqrt{U^2 + V^2}$, (d) Reynolds shear stress, $\langle u'v' \rangle$ [cm$^2$s$^{-2}$]

velocity. The flow was generated by an oscillating grid creating an unsteady, pulsing flow with velocity fluctuations, that were calculated as r.m.s. turbulence fluctuations causing higher r.m.s. values for the lower frequencies. In Figure 5(b) the turbulent intensity for 2.0Hz and 2.5Hz is approximately 0.8, indicating a turbulent flow, however for the lower frequencies, 1.3 Hz and 1.7 Hz, the turbulence intensity is higher than 1, which is unreasonable. Furthermore, in Figure 4(d), the magnitude of the Reynolds stress obtained for lower frequencies, 1.3 Hz and 1.7 Hz, is considerably lower than the values obtained for 2.0 Hz and 2.5Hz. Therefore, in the lower frequencies we observe a transitional type of flow.

Hence, one cannot consider the r.m.s velocity as the individual parameter characterizing the resuspension process, without giving attention to the nature of the flow in question.

3.3. 3D-PTV results

The major results of particle tracking velocimetry experiments are Lagrangian trajectories defined as locations of particles in time and space. In Figure 5(a), we present three orthogonal views and an isometric sketch of the Lagrangian trajectory, demonstrating the incipient motion of a particle as it moves upwards, obtained for frequency of 1.3 Hz, water depth 13 cm. Coordinates
are given in millimeters, with respect to the origin predefined by the calibration target, $y$ is the vertical direction. Figure 5(b) demonstrates quantitative analysis of the position and velocity and acceleration of the resuspended particle in $x,y$ and $z$ directions in time. Both figures illustrate the particle’s complex movement: at the beginning of the motion for about 0.5 sec, the particle moves only in the $x$ and $z$ direction, which means that it is either sliding or rolling on the bottom and only then lifted off and entrained into suspension. After pick up, the velocity and acceleration, although not high, change in all directions consistently, resulting in a 3D motion in a corkscrew pattern. It is noteworthy that this method allows to determine in a direct and quantitative way whether the particle is in the saltation or resuspended mode. These two modes are different by the values of positive or negative vertical acceleration during the period of re-entrainment.

Variability in experimental results This study has shown relatively small changes in resuspension ratios for runs repeated under the same experimental conditions, as compared to the results typically presented in similar studies. The experimental variability was assessed by repeating experiments under virtually the same conditions. The uncertainty in PIV results are about 5% for the mean flow fields and about 10% for the fluctuating velocity quantities. The uncertainty in the oscillating grid frequency is below 1%. The resuspension ratio $\eta(t)$ is the least accurate result and it varies within the range of $\pm 20\%$. The relatively small scatter in the presented results is due to a type of the experimental facility without a mean through flow and is also due to precise control of the important conditions.

4. Summary and conclusions

Our primary goal is to explore in a quantitative manner the necessary flow conditions for initial entrainment of spherical particles from a smooth bed into zero-mean-shear turbulent flow in an oscillating grid chamber, and to track the movement of individual particles through the various phases of the resuspension. An ultimate experiment will eventually combine two 3D-PTV systems that will simultaneously measure the turbulent flow conditions along with the acceleration (i.e. forces) experienced by the detached particle. The present results are preliminary and describe the relation of the particle motion to the surrounding fluid dynamics in a statistical sense only.

During the visualization stage different patterns of resuspension were observed, while the total number of resuspended particles increased with the increasing frequency of the grid. In the lower frequencies (1.3 Hz and 1.7 Hz), most particles were lifted off individually, while for the higher frequencies (2.0 Hz and 2.5 Hz), the particles were more likely to suspend in groups. For the higher frequencies, these results suggest that the particle movement occurs in patterns, where particles are more likely to move when other particles are moving. Additionally, this could be related to turbulence coherent motions, such as bursts, e.g. Heays et al. (2010). From the modeling point of view, this fact requires some information about four-way coupling of the particles and the flow: two-way coupling of particle with a fluid, fluid-bed interaction and the inter-coupling of the particles. From the experimental point of view, this fact will add another layer of complexity to the simultaneous measurements with two tracking systems.

Shvidchenko & Pender (2000) suggested that critical flow conditions for uniform sediment motion are dependent not only on the grain size, but also on the ratio of flow depth to grain size. We also tried to emphasize that the total depth of water in the tank plays some role, but the results were not conclusive enough to draw a single conclusion. In general, we note that the experiments that define detachment or resuspension ratios need to be performed and compared at exactly the same conditions. Introducing the influence of static pressure (i.e. the water column) into the resuspension models might improve the prediction capability of sediment
Figure 5. (a) Three orthogonal views and an isometric sketch of the Lagrangian trajectory of the resuspended particle. (b) Position, velocity and acceleration of the resuspended particle during the incipient motion and pick-up phases.
transport models.

Results from the 3D-tracking provided quantitative information on the $x$, $y$, and $z$ positions, velocity, acceleration and duration of the movement for any moving particle in the test section. It assists our understanding of the different possible modes of particles resuspension and helps to quantify the effects of rolling/sliding on the following detachment. However, without special color-coding of the particles under investigation, it is difficult to distinguish between the rolling and sliding modes.

Our results show also a clear relation between the mean velocity magnitude and the number of suspended particles, however it can not explain by itself particle incipient motion. The Reynolds shear stress and the turbulent intensity obtained for the lower frequencies indicate a not fully developed, transitional turbulent flow, while for the higher frequencies we observe fully developed turbulent flow regime. Since we obtained more resuspension events in the higher frequencies, the number of which correlates positively with the Reynolds shear stress results, we can infer that intrinsic correlations present in turbulent flows play an important role in the initiation of particle motion. Our results do not fully support the proposition of Clifford et al. (1991, among others), that the normal stress component, $u'^2$, is the important parameter in the mobilization of sediment. We notice that the simple measures of turbulent intensity are not sufficient and require some additional information about the turbulence nature, e.g. the Reynolds shear stress $\langle u'v' \rangle$ or similar. Further study is necessary in order to verify this hypothesis.

5. Acknowledgments

This work is supported in part by the Israel Science Foundation under grant 782/08, the Wolfson Family Charitable Fund, Tel Aviv University and MISTI student exchange program. The authors are thankful to the team of the Turbulence Structure Laboratory at the School of Mechanical Engineering for the assistance with the experiments.

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