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DIRECT NUMERICAL SIMULATION OF PARTICLE SALTATION IN TURBULENT CHANNEL FLOW

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This paper reports on the numerical investigation of particle saltation in a turbulent channel flow having a rough bed consisting of 2-3 layers of densely packed spheres. The Shield’s Function is 0.065 which is just above the sediment entrainment threshold to give a bed-load regime. The applied methodology is a combination of three technologies, i.e., the direct numerical simulation of turbulent flow, the combined finite-discrete element modelling of the deformation, movement and collision of the particles, and the immersed boundary method for the fluid-solid interaction. It is shown that the presence of entrained particles significantly modifies the profiles of flow velocity and turbulent intensities in the vicinity of a rough-bed. Statistical features of particle translational and angular velocities, together with sediment concentration and volumetric flux density profiles, are presented.

INTRODUCTION

In the bed-load layer, sediment may be transported via three modes: sliding, rolling or saltation and the last one is considered to be the most dominant [1]. Particle saltation in turbulent channel flow has been experimentally investigated for several decades. Many statistical features, such as saltation length and height, mean particle stream-wise velocity, incidence and take-off angles at collision, dynamic friction coefficient, etc., were reported in the work of van Rijn [2], Abbott & Francis [3], Niño & García [4], Niño et al. [5], Lee et al. [6,7]. However, higher-order statistics of the particle translation and rotation, the hydrodynamic forces and moments acting on the particles and the statistical features of the particle-laden horizontal turbulent channel flow have not been studied adequately due to the fact that they are very difficult, if not impossible, to be measured directly.

Besides experimental studies, several different theoretical models were presented by Lee et al. [6], Osanloo et al. [8] and Niño & García [1]. These models are based on Newton’s second law and some parameters, such as drag and lift coefficients, restitution and friction coefficients, incident and take-off angles, etc., are determined experimentally and reasonable results on the first-order statistics were obtained. However, the fluctuation in particle trajectories caused by the turbulent coherent structures and the diversity of take-off angles owing to the random packing arrangement of particles forming the rough bed were not reproduced.
With the development of high performance computing technology and numerical schemes, sediment transport simulation in which the particles are well-resolved by grids presents an effective way not only to investigate the interaction between particle motions and near-bed turbulence structures, but also to show the dynamic process of particle saltation in detail in which the hydrodynamic forces and moments, collision between particles and pressure distributions on the particle surface are investigated.

Chan-Braun et al. [9] numerically investigated the hydrodynamic forces and torques on spherical particles fixed on a bed consisting of one layer of spheres in a square arrangement using a combination of direct numerical simulation (DNS) for the turbulent flow and the immersed boundary method (IBM) for the fluid-solid interactions. Chan-Braun et al. [10] and Kidanemariam et al. [11] further investigated the statistical features of finite-size heavy particles’ transport in turbulent open channel flow. Shao et al. [12] carried out a fully resolved DNS of particle-laden turbulent flow in a horizontal channel by using the direct-forcing fictitious domain method which is closely related with IBM. Ji et al. [13] studied the interaction between turbulent coherent structures and particle entrainment by coupling DNS and the IBM together with the combined finite-discrete element method (FDEM) which takes into account particle deformability, frictional contact forces, and frictional and plastic-loss of energy. Particle movement, hydrodynamic forces and turbulent flow statistics at the incipient of entrainment were reported. These results contributed greatly to the understanding of the underlying physical mechanisms of particle transport in turbulent channel flow.

This paper further investigates the subsequent continuous saltation after the particles have been entrained by the turbulent coherent structures. It reports on the statistical features of particle translational and angular velocities, together with sediment concentration and volumetric flux density profiles.

**METHODOLOGY**

The applied methodology is three-fold. The code used to simulate the turbulent flow is an in-house computational fluid dynamics (CFD) C code called CgLes [14]. It is a 3D DNS/LES (large eddy simulation) code with second order accuracy in both time and space. The immersed boundary method, first introduced by Peskin [15] in the simulation of blood flow around the flexible leaflet of human heart, was incorporated into CgLes to model the interaction between the flow and moving particles. The main advantage of the IBM is associated with its inherent simplicity in treating flows which have solids with moving boundaries. To improve the accuracy of the IBM, an iterative direct-forcing IBM which was introduced in our previous work [16] is applied in this study. To simulate the movement and collision of particles, we coupled CgLes with another in-house combined finite-discrete element method C code developed by Munjiza et al. [17]. This code comprises a set of C libraries incorporating the latest breakthroughs in discontinua simulations. It is capable of modelling the deformation, movement and collision of millions of particles of different shape and size.

**STATISTICS OF TURBULENT FLOW AND PARTICLE TRANSPORTATION**

**Problem description**

In this study, we considered sediment transport in a fully developed turbulent open channel flow having a rough bed consisting of 2-3 layers of densely packed spheres (see Fig. 1). The total number of spheres was 6355 and the rough bed was water-worked meaning that the most
exposed ones were removed. No-slip boundary conditions were used on both the bed and sphere surfaces and the top boundary was set as a free-slip hard lid. Periodicity was imposed in both the stream-wise and span-wise directions. The following list summarizes the simulation parameters:

- Computational domain sizes in x, y and z directions: $6d \times d \times 4d$;
- Number of grid nodes in x, y and z directions: $960 \times 160 \times 640$;
- Grid spacing in wall units: $\Delta x^+ = \Delta y^+ = \Delta z^+ \approx 5.4$;
- Kolmogorov length scale in wall units: $\eta^+ \approx 3.3$;
- Particle diameter: $D_d = 0.1$;
- Geometric height of roughness elements: $k = 0.3d$;
- Equivalent roughness height: $k_e = 0.242d$;
- Effective bed location: $y_b = 0.252d$;
- Effective channel depth: $h = d - y_b = 0.748d$;
- Density ratio: $\rho_s / \rho_f = 2.65$;
- Shields function: $\Theta = \tau_u / ((\rho_s - \rho_f)gD) = 0.065$;
- Reynolds number: $Re^*_D = u_l h / \nu = 647$;
- Particle Reynolds number: $Re^*_p = u_p D / \nu = 86.5$;
- Equivalent roughness height in wall units: $k_e^+ = k_e u_l / \nu = 209$;
- Reynolds number based on bulk velocity: $Re^*_b = U_b h / \nu = 6417$;
- Reynolds number based on velocity on the top surface: $Re^*_c = U_c h / \nu = 8078$.

In the above, $d$ is the channel depth, $\nu$ is the fluid kinematic viscosity, $g$ is the gravitational acceleration, $U_b$ and $U_c$ are the bulk velocity and the velocity on the top surface respectively, $\rho_s$ and $\rho_f$ are the densities of particle and fluid respectively, $u_l$ and $\tau_u$ are the friction velocity and the shear stress at $y_b$ respectively, superscript ^+ indicates quantities in wall units $l = \nu / u_l$. Note that a different definition of $u_l$ has been applied in this study compared with that of Ji et al. [16] which, consequently, makes $Re^*_D$, $Re^*_p$ and $k_e^+$ smaller.

To facilitate the following analysis and discussion, the following terminology is adopted: single-phase flow indicates the turbulent channel flow over the fixed rough-bed and two-phase flow denotes the turbulent channel flow with sediment transport. The fluid phase of the two-phase flow represents the flow in the whole computational domain excluding the volume occupied by spheres regardless of their state of motion whilst the dispersed phase of the two-phase flow is the moving spheres. Furthermore, a vertical coordinate $Y = y - y_b$ is adopted, where $y$ is the vertical coordinate and $y_b$ is the effective bed location.
Statistical features of the two-phase turbulent flow

Figure 2 shows the plane (binned) and time-averaged stream-wise velocity of the fluid (dispersed) phase of the two-phase flow, together with that of the single-phase flow for comparison. Here, the plane averaging of Eulerian quantities on the DNS grids was performed over the fluid-occupied domain in the wall-parallel planes and the binned averaging of the Lagrangian quantities related to particles was performed over the particles with their center in the wall-parallel bins with a thickness of $D/10$. As seen in Figure 2, the velocity profile of the fluid phase is retarded above the highest crests of the roughness elements of the single-phase flow case (referred to as P1, hereafter), comparing with that of the single-phase flow, due to the presence of the entrained particles. Below this position, the flow is accelerated because the moving particles cause less momentum exchange with the fluid phase. The mean stream-wise velocity of the dispersed phase is always smaller than that of the fluid phase and shows a quasi-linear profile although there are small fluctuations in the top region of the bed-load layer due to the sampling of an insufficient number of particles visiting there. The height of the bed-load layer, calculated as the distance from the effective bed location of the single-phase flow case (referred to as P2, hereafter) to the highest position that moving particles’ center can reach, is approximately $0.29h$ (2.1D). The mean velocity profile of the fluid phase verifies the logarithmic law-of-the-wall above $Y/h = 0.29$, as shown in the inset of Figure 2. However, the transition from a concave curve to a convex one as shown in the mean velocity profile of the single-phase flow is absent from the mean velocity profile of the fluid phase.

Figure 2. Comparison of the mean stream-wise velocity profiles.

Figure 3. Comparison of turbulence quantities between the single and two-phase flow cases.
Figure 3 shows the turbulence quantities for both the single and two-phase flow cases. The modifications to the turbulence quantities due to the presence of the dispersed phase is clearly seen, especially near and below P1. Specifically, the near-wall peak of the stream-wise component  of the fluid phase is smoothed and shifted downward and also decreases slightly in magnitude compared with that of the single-phase flow. This is in agreement with the experimental results of Kiger & Pan [18] and the numerical results of Chan-Braun et al. [10] and Shao et al. [12]. However, the fluid velocity fluctuations deviate only marginally from the single phase counterpart in the numerical results of Kidanemariam et al. [11] which is attributed to their small solid volume fraction of 0.05%. It should be noted that the near-wall peak values of  for the single and two-phase flow cases of the present study are approximately 2.1 and 2.0, respectively, which are much lower than the value of 2.7 for the particle-free and particle-laden cases in Kidanemariam et al. [11], owing to the near-wall coherent streaky structures of turbulent flow being destroyed by the large particle size and solid volume fraction in the present study. This lower-peak trend is also shown in the results of Shao et al. [12] and becomes more pronounced with increasing particle size and solid volumetric fraction. The span-wise velocity fluctuations of the two-phase flow are only marginally different from the single-phase case. However, the vertical velocity fluctuations show a perceivable increase which could be the result of high-speed particles in the outer region landing and colliding on the rough-bed and introducing small-scale vortices in the near-wall region. Below P2, the turbulence intensities of the single-phase flow show small fluctuations, while the ones of the two-phase flow are smoother.

In contrast to their counterparts of the fluid phase, the turbulence intensities of the dispersed phase in the vertical and span-wise directions are almost identical in the near-wall region where the greater occurrence of collisions leads to a more isotropic distribution of sphere fluctuation energy in the vertical and span-wise directions and is in agreement with the findings of Chan-Braun et al. [10] and Kidanemariam et al. [11]. The stream-wise component is generally larger than the other two and, above 0.2, large fluctuations are observed in all three components due to insufficient number of samples. All three turbulence intensities of the dispersed phase are consistently smaller than their fluid phase counterparts and is a result that does not agree with the findings of Chan-Braun et al. [10] who found that the vertical velocity fluctuations of the dispersed phase are larger than their fluid phase counterparts in the near-wall region, and also the findings of Kidanemariam et al. [11] who found that both vertical and span-wise velocity fluctuations of the dispersed phase are larger than their fluid phase counterparts. This discrepancy could be due to the lower solid-fluid density ratio, i.e.,  and the smaller grain-size in their study - lighter and smaller particles are more easily accelerated by the surrounding flow, and their motion thus more turbulent.

Statistics of translation and rotation of the entrained particles
Figure 4 shows the binned and time-averaged velocity components of the dispersed phase. The mean vertical and span-wise velocity profiles are almost zero throughout the channel depth, despite the small fluctuations observed in the top region of the bed-load layer. The volumetric flux density function  and the sediment concentration  are also presented in Figure 4 in which  and  are normalized by  and , respectively, where  is the average sediment concentration of the static rough-bed. The flux density shows a symmetric profile and peaks at P1. Beyond that, the flux density function and the sediment concentration decrease exponentially with height and agrees with the numerical results of Durán et al. [19].
The non-dimensional volume flux \( \phi = q_s / \sqrt{(\rho_s / \rho_f - 1)gD^3} \) is 0.0327 which agrees well with experimental data and several well-known bed-load transport equations’ values, ranging from 0.01 to 0.04, at \( \Theta = 0.065 \) compiled by Wiberg & Smith [20] (refer to Fig. 7 of their work). The volumetric sediment flux \( q_s \) is calculated according to \( q_s = \pi D^3 / (6A) \sum \overline{v}_p \), where \( A \) is the channel area and \( \sum \overline{v}_p \) is the sum of mean velocity over all spheres. It should be noted that \( \overline{U}_p \) indicates the binned and time-averaged stream-wise velocity of the dispersed phase whereas \( \overline{v}_p \) represents the time-averaged stream-wise velocity of an individual particle.

Figure 5 shows the binned and time-averaged angular velocities, normalized by \( u_r / D \), of the dispersed phase. The mean stream-wise and vertical angular velocities, i.e. \( \omega_x \) and \( \omega_z \), are generally zero except fluctuations in the top region of the bed-load layer, while the one in the span-wise direction \( \omega_y \) decreases with height and reaches a negative plateau with \( \omega_y D / u_r \approx 2.2 \) before it plummets at \( Y / h \approx 0.23 \) owing to the insufficient sampling. The negative span-wise angular velocity indicates that the entrained particles predominately rotate clockwise in the x-y plane (flow is from left to right).

All standard deviations of the angular velocities show a similar trend except that the span-wise component, \( \sigma_{\omega_y} \), have a larger value – see Figure 6. Below the effective bed location \( \sigma_{\omega_x} \approx \sigma_{\omega_z} \), while \( \sigma_{\omega_y} > \sigma_{\omega_z} \) beyond that. This is due to the fact that the \( y \)-rotation of particles is caused by the relative velocities in \( z \) and \( x \) directions of contacting particles while the \( x \)-rotation is related with those in \( y \) and \( z \) directions and the fact that the mean velocity and its standard deviation in \( x \) direction are much larger than those in \( y \) and \( z \) directions – see Figures. 3 and 4.
CONCLUSIONS

In this study, particle saltation in a turbulent channel flow has been numerically investigated using a methodology which combines the DNS of turbulence flow, the FDEM of particle dynamics and the IBM for the fluid-solid interaction. Statistics of the particle-laden turbulent flow, particle translation and rotation, together with the sediment concentration and the volumetric flux density profiles, have been presented. It was found that the presence of the dispersed phase significantly modifies the statistical features of the turbulent flow in the vicinity of the rough-bed. For example, our numerical results have showed a distinct velocity lag between the single and two-phase mean stream-wise flow profiles and the reason has been attributed to a larger particle size and solid volume fraction. The particles’ mean stream-wise velocity shows a quasi-linear profile, while their mean angular velocity in the span-wise direction is almost constant.

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