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Transition to turbulence in the presence of finite size particles

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Abstract

We study the transition from laminar to turbulent flow in a channel seeded with finite-size neutrally buoyant particles. A fixed ratio of 10 between the channel height and the particle diameter is considered. The flow is examined in the range of Reynolds numbers $500 \leq Re \leq 5000$ and the particle volume fractions $0.001 \leq \Phi \leq 0.3$. We report a non-monotonic behavior of the threshold value of the Reynolds number above which the flow becomes turbulent, in agreement with previous experimental studies. The mean square velocity fluctuations and Reynolds shear stress of the fluid phase are reduced by increasing the particle volume fraction at a fixed Re=1500, while the mean square velocities of the solid phase are enhanced monotonically suggesting a transition from fluid to particle dominated dynamics at high volume fraction.

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1. Introduction

The transition from laminar to turbulent flow is the object of numerous investigations owing to the significant alteration observed in the nature of the flow and the following sudden increase of the drag [1]. Despite the vast number of investigations, this phenomenon is still not throughly understood, especially in channel flows where the transition is subcritical and occurs at Reynolds numbers lower than that predicted by linear stability analysis. Transition takes place when strong enough perturbations are present in the flow due to the action of internal or external excitations.

The aim of the current work is to numerically investigate the effect of suspended finite-size (larger than the smallest flow scale) particles on the transition to turbulence in a channel flow. Suspension of particles can be found in different industrial and environmental applications: transport of cement and slurries in pipelines and sediments in river beds. In this work, we aim to relate our results to the experimental observations by Matas et. al. [2] on the transition of particulate pipe flow. For the small ratios of the pipe to particle diameter, $D/(2a) \leq 65$, they found a non-monotonic behavior of the critical transition threshold when increasing the volume fraction: the critical Reynolds number first decreases and than increases. The need to better understand the behavior of inertial suspensions has been addressed among others

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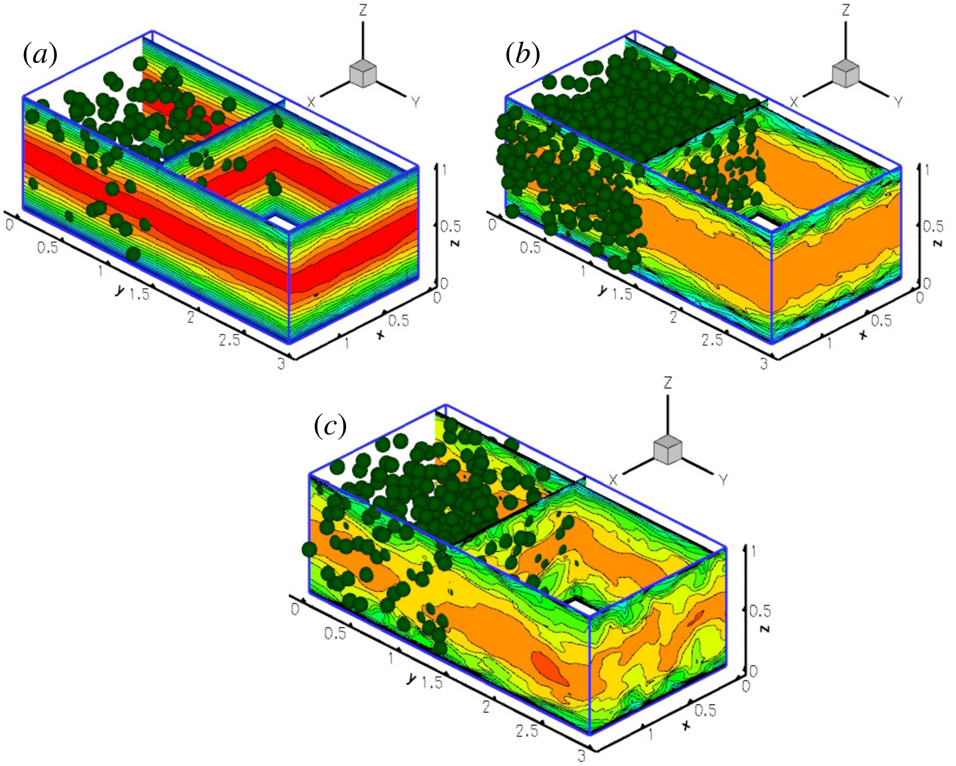

Fig. 1. Instantaneous flow field at (a) Reynolds number $Re = 500$ & volume fraction $\phi = 0.05$, (b) $Re = 2500$ & $\phi = 0.3$ and (c) $Re = 5000$ & $\phi = 0.1$. Only particles located in the half of the domain are shown for clarity

in the review by Koch and Hill[3] and recent developments in the direct numerical simulation of multiphase flows can lead to new insights.

We adopted an Immersed Boundary method, originally proposed by Uhlmann[4], that couples the uniform Eulerian fixed mesh for the fluid phase with a Lagrangian mesh for the solid phase to trace the surface of the particles in the fluid. In particular, we employ the solver developed by Breugem[5] achieving second order spatial accuracy. Lubrication corrections and a soft-sphere collision model have been implemented to address the short-range interactions occurring below the typical mesh size. The code has been recently used by Picano *et. al.*[6] and Lambert *et. al.*[7] to study the rheology of dense and active suspensions and by Lashgari *et. al.*[8] to investigate the inertial effects on the transitional particulate channel flow.

The simulations have been performed in a plane channel with periodic boundary conditions in the streamwise and spanwise directions. Here we denote the streamwise coordinate and velocity by y and v, the wall-normal by z and w and the spanwise by x and u. The size of the computational domain is $2h \times 3h \times 6h$ in wall normal, spanwise and streamwise directions where h is the channel half width. We choose a fixed particle diameter, $2a = 2h/10$ corresponding to the experimental data where the strongest non-monotonic behavior is observed for the critical threshold[2]. We have used 16 Eulerian points per particle diameter and about 800 Lagrangian points per particle surface to fully resolve the coupling between the fluid and solid phase. The number of uniform Eulerian grid points in the domain is $160 \times 240 \times 480$ in wall-normal, spanwise and streamwise directions. The Reynolds number is defined by the bulk velocity and channel height; we study wide range of parameters, Reynolds number $500 \leq Re \leq 5000$ and particle volume fraction $0.001 \leq \Phi \leq 0.3$. The highest number of particles in the simulations is 2580 for the largest volume fraction studied, $\Phi = 0.3$. The initial condition for the simulations is chosen to be a high amplitude localized disturbance in the form of pair of streamwise vortices with the maximum wall-normal velocity equal to unity[9]. In a suspension of finite-size particles there is no scale separation and inertia crucially affects both fluid and particle phases[3].

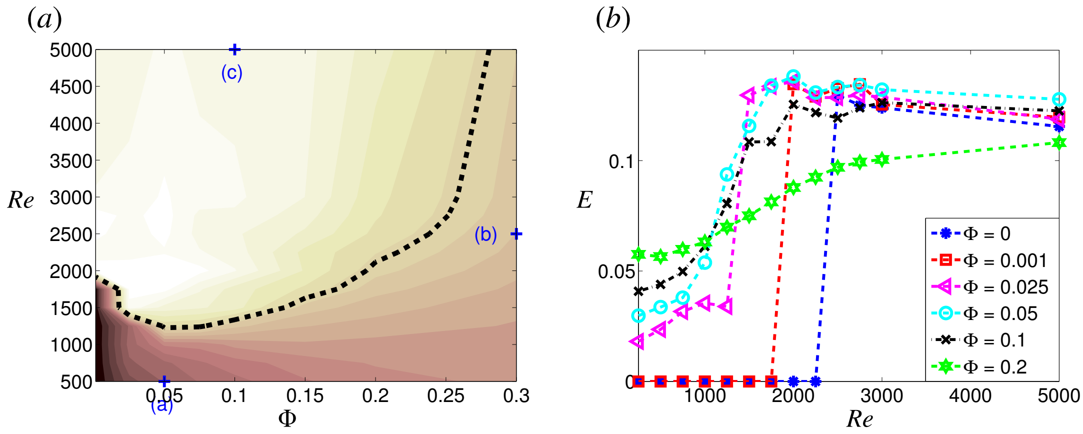

Fig. 2. Ensemble-average of the velocity fluctuation kinetic energy (a) contour map of $Re - \Phi$ plane (b) versus Reynolds number for fixed particle volume fraction Φ

2. Results

For the particulate flow, since the flow is disturbed by finite-size particles, fluctuations are expected to be present even at very low Reynolds numbers and consequently the distinction between the flow regimes becomes more difficult. Recently, Lashgari *et. al.*[8] studied the transitional particulate flow of finite-size neutrally buoyant particles and observed three different regimes, laminar-like, inertial shear-thickening and turbulent-like by varying the Reynolds number and particle volume fraction at a fixed particle diameter. The laminar-like regime is characterized by the strong contribution of the viscous stress in the total stress budget, while in the turbulent-like regime the Reynolds stress plays a major role in transporting momentum. The cases of high particle volume fraction exhibit inertial shear-thickening where a significant increase in wall shear stress is observed not due to the enhancement in Reynolds shear stress but to the increase in particle stresses.

We display the instantaneous flow field in figure 1 for three simulations corresponding to the three different regimes introduced in Lashgari *et. al.*[8]. The contour of the streamwise velocity (mixed of fluid and particle velocity) is displayed together with the particle arrangements only in half of the domain for the sake of clarity. Figure 1(a) shows the laminar-like flow at $Re = 500$ and $\Phi = 0.05$, where the flow is slightly perturbed by the particles and the mean velocity distribution is similar to the laminar flow. The particles distribution does not show any preferential accumulation in the domain. Figure 1(b) represents the inertial shear-thickening regime at $Re = 2500$ and $\Phi = 0.3$ where the flow is chaotic and particles tend to concentrate in the center of the channel as well as in a layer close to the wall. The migration of the spherical particles to the center of a pipe has been observed in the work by Hampton[10] in slow pressure driven flow and for high volume fractions, $\Phi > 0.2$. Figure 1(c) displays the turbulent-like regime at $Re = 5000$ and $\Phi = 0.1$ where the flow is similar to a turbulent flow and the distribution of the particles is more uniform.

To quantify the behavior of the flow in the different regimes we examine the kinetic energy of the perturbations (mixed of fluid and solid phases) once the mean quantities are statistically converged. The $Re - \Phi$ contour map of the ensemble-average of the perturbation kinetic energy, E, is depicted in figure 2(a). The iso-level blue dashed-line corresponds to a particular value of $E = 0.09$ showing the non-monotonic variation of the perturbation kinetic energy by changing the volume fraction, inline with the experimental findings reported in Matas *et. al.*[2] . The points (a), (b) and (c) correspond to the three different cases of figure 1 and the perturbation kinetic energy of $E = 0.0337$, $E = 0.0788$ and $E = 0.1225$ respectively. In figure 2(b), we extract vertical lines of the data form the contour map at some volume fractions. For low values of volume fractions, $\Phi \leq 0.05$, the transition threshold is evident through a sharp jump of the average kinetic energy in the domain. Interestingly, the critical Reynolds number is decreasing when increasing the particle volume fraction in this regime while the level of fluctuations after the transition lies on the same regime values. The reduction in the critical threshold is attributed to the disturbances induced by particles (see also Matas. *et. al.*[2]) and it is explained by the breakdown of the coherent structures into numerous more energetic

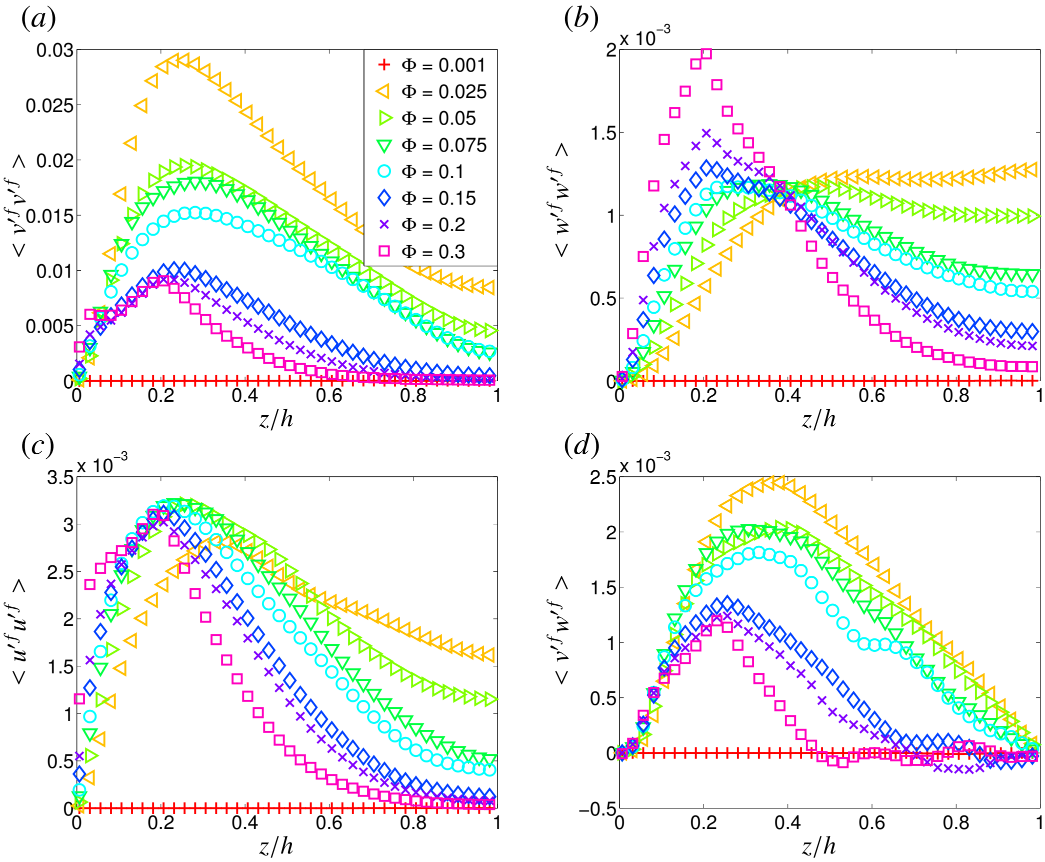

Fig. 3. Mean square of fluid velocity fluctuations in (a) streamwise (b) wall-normal (c) spanwise directions and (d) fluid Reynolds shear stress

eddies (see Loisel *et. al.*[11]). For $0.05 < \Phi \leq 0.1$, the level of the fluctuation increases at low Reynolds numbers and the transition appears to be smooth and extends over a wider range of the Reynolds numbers. It is worth mentioning that the level of the fluctuations at high Reynolds number reaches the same value suggesting a turbulent-like state. For $\Phi = 0.2$, the transition region is more smooth and the perturbation kinetic energy only slightly increases with the Reynolds number. In this case the level of fluctuations does not reach the one of the single-phase turbulent flow even at high Reynolds numbers.

We quantify in more details the dynamics of the flow in the suspensions, considering both fluid and particle phases. We analyze the single point statistic of the fully developed suspension for the cases at fixed $Re = 1500$ and varying Φ. The choice of the Reynolds number is based on the data on the contour map in fig 2 where we observe a non-monotonic behavior in the perturbation kinetic energy of the suspension by increasing the particle volume fraction. Following the framework introduced by Marchioro *et. al.*[12] and Zhang & Prosperetti[13], the mean square (intensity) of the velocity fluctuations and Reynolds stress of the two phase flow can be expressed in the form of a combined (single phase) flow, $< u_i'^c u_j'^c >= (1 - \phi(z)) < u_i'^f u_j'^f > + \phi(z) < u_i'^p u_j'^p >$, where $\phi(z)$ is the local particle volume fraction as a function of wall-normal coordinate and superscripts f and p refer to the fluid and particle phase respectively. In this work, we examine separately the contribution of the fluid and particle phase in the total mean square velocity fluctuations and Reynolds stress of the suspension.

In figure 3 we show the profile of streamwise, wall-normal and spanwise mean square velocities together with Reynolds shear stress for the fluid phase as a function of wall-normal coordinate. Note that the data of fluid phase are weighted by $(1 - \phi(z))$ and are normalized by the mean bulk velocity. For very dilute suspension, i.e. $\Phi = 0.001$, viscous dissipation damps the fluctuations induced by the particles and the flow remains laminar at $Re = 1500$. Once we increase the number of particles in the flow, the disturbances become more pronounced and the flow experiences

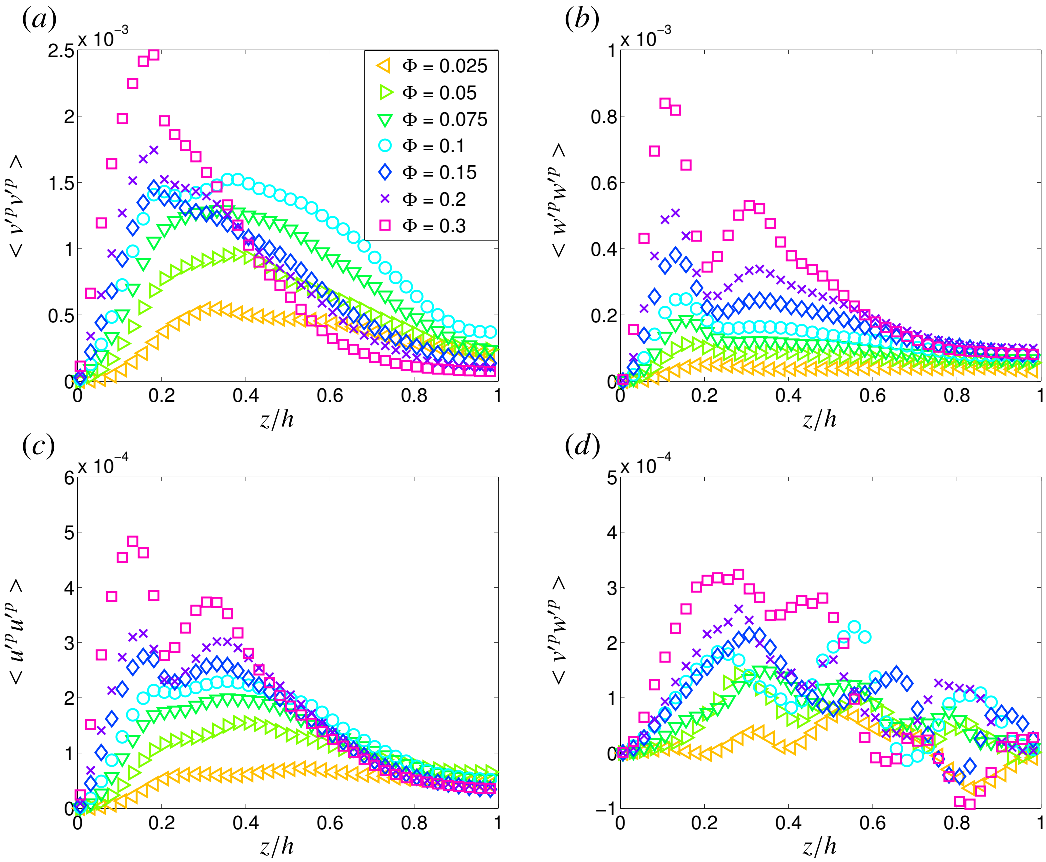

Fig. 4. Mean square of particle velocity fluctuations in (a) streamwise (b) wall-normal (c) spanwise directions and (d) particle Reynolds shear stress

a sharp transition form laminar to turbulent regime where high amplitude velocity fluctuations are sustained in the system. The location of the maximum streamwise mean square velocity (see figure 3 a) remains unchanged, however, the level of the fluctuations monotonically decrease by increasing Φ. The cross flow velocity fluctuations exhibit a significant reduction in the core region by increasing the particle volume fraction. The accumulation of the particles in the core region, especially for the cases with high volume fraction, damps the fluid velocity fluctuations considerably (almost zero Reynolds stress at $z/h > 0.5$) and reduces the local particle volume fraction at $z/h < 0.4$ where higher probability of squeezing motion between the particle pairs and particle-wall interactions promote disturbances. The disturbances in the near wall region are less efficiently damped by the action of viscous dissipation. In figure 3(d) we show that the turbulence production (Reynolds shear stress) is also reduced due to the dissipation induced by hydrodynamic interactions between the particles and fluid phases as suggested by Matas *et. al.*[2]. Surprisingly, the reduction in turbulent activity is accompanied with an enhancement in wall shear-stress (the effective viscosity of the suspension) and this can be related to the dynamics of the particles. The peak of the fluctuations in the case of volume fraction, $\Phi = 0.3$, is located at $z/h = 0.2$ corresponding to the layering of the particles with diameter of 0.2 at the wall.

The particle mean square velocity fluctuations and particle Reynolds shear stress across the channel are shown in figure 4 for $Re = 1500$ where the data are weighted by $\phi(z)$. In general the fluctuations are much lower for the particle phase than the fluid phase suggesting that the momentum is transferred across the channels mainly by the fluid and the ballistic motion of the particles in the wall normal direction is less important. Therefore the profile of the velocity fluctuation intensity and Reynolds stress of the combined phase (the sum of the curves in figure 3 and 4) are very similar to those of the fluid phase (see figure 5). Opposite to the fluid phase, the particle phase is characterized by a monotonic increase in the level of fluctuations by increasing Φ as it is expected because of the increment in $\phi(z)$ (not shown) and particle-particle interactions. At the core of the channel the fluctuations are negligible even though

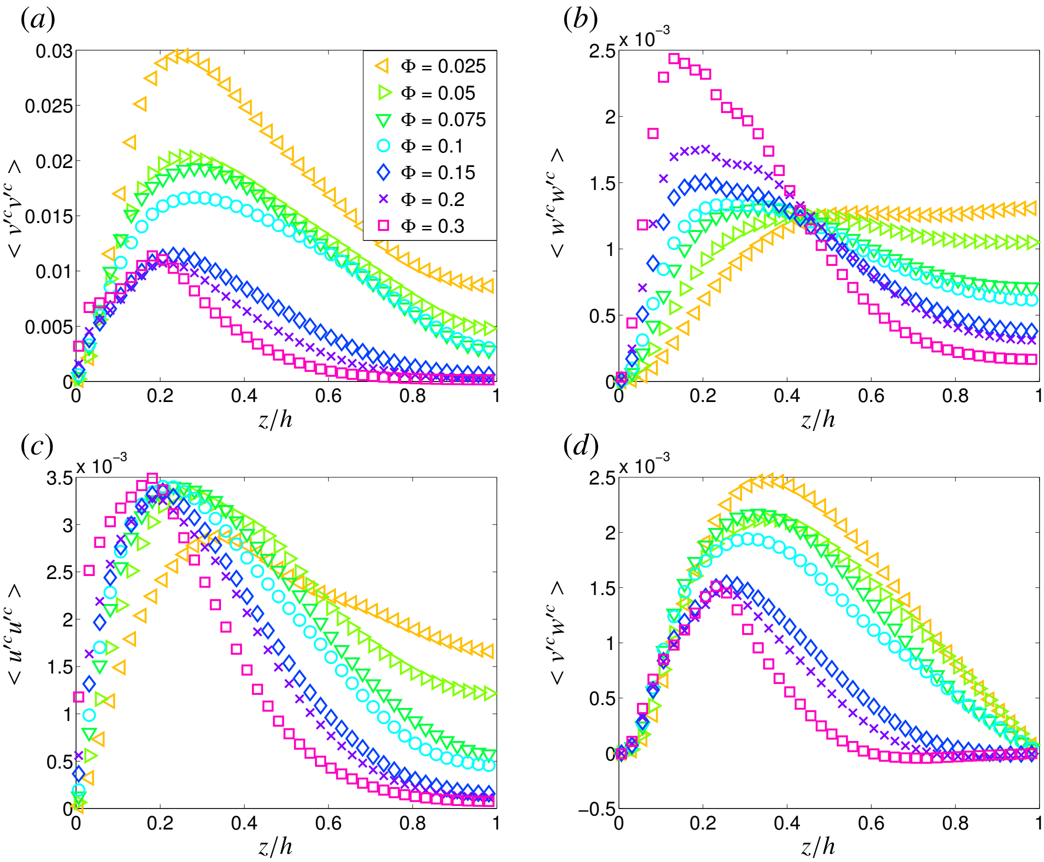

Fig. 5. Mean square of combined (total) velocity fluctuations in (a) streamwise (b) wall-normal (c) spanwise directions and (d) particle Reynolds shear stress

the local particle volume fraction is high especially for the cases of high Φ. This indicates that the transport of the particles in the streamwise direction is by a laminar-like (low fluctuation) carrier fluid. Once the particles enter the central region, they tend to stay and are transported by the flow. Close to the wall, the cross stream fluctuations reproduce the layering of the particles while the streamwise fluctuations display the particle sliding. Particles feel more freedom in the motion in the wall normal direction at $z/h < 0.5$, resulting in high values of particle mean square velocities and Reynolds stress.

3. Conclusion

In summary, numerical simulations of channel flow suspended with neutrally buoyant finite-size particles have been performed for a fixed ratio of 10 between the channel height and particle diameter and the non-monotonic behavior of the critical threshold of the transition, as in experiments, reproduced. The mean square velocity fluctuations and Reynolds shear stress of the fluid phase shows a monotonic reduction by increasing the particle volume fraction at $Re = 1500$. The crossflow fluid velocity fluctuations increases in the near wall region due to the enhancement of the squeezing motion resulting from particle-particle and particle-wall interactions while the fluctuations tend to zero in the core region due to the significant particle accumulation. The opposite behavior is observed for the mean square velocity fluctuation and Reynolds stress of the particle phase that monotonically increases by increasing the number of particles in the suspension. This enhancement in the particle fluctuations is limited to the wall region where the particles are freely moving in the wall-normal direction opposite to the core of the channel where a laminar-like flow transports the particles downstream.

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