EFFECTS OF WALL ROUGHNESS IN A GAS-PARTICLE TURBULENT VERTICAL CHANNEL FLOW

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ABSTRACT

Gas-particle turbulent channel flows are studied using the Lagrangian particle tracking coupled with large eddy simulation (LPT-LES). A turbulent channel flow of air at $Re_\tau = 644$, loaded with 70 μm copper particles at a mass fraction of 2 % and a flow with 50 μm glass particles at the same condition are simulated. Small amount of roughness is introduced at the walls and its influence on the statistics of particles is investigated. The statistics of the highly inertial particles, i.e. 70 μm copper particles, are found to be largely modified in the whole channel due to the presence of the wall roughness, and a tendency similar to the experimental data by Kulick et al. (1994) is observed. The statistics of the particles with smaller inertia, i.e. 50 μm glass particles, are less influenced by the wall roughness assumed in the present study.

INTRODUCTION

The Lagrangian particle tracking coupled with direct numerical simulation (LPT-DNS) or that with large eddy simulation (LPT-LES) is expected to be able to predict gas-particle turbulent flows with high accuracy. Studies using such LPT simulations have extensively been done for the unbounded flow such as isotropic turbulence, turbulent jet and homogeneous shear turbulence all laden with particles. For the practical applications such as combustion, food transport and efficient heat exchanging process using gas-particle flow, an accurate prediction of such flows in geometries bounded by rigid walls is of the greatest importance. However, in the cases with inertial particles in a wall-bounded flow, previous one-way coupling LPT simulations assuming elastic rebounce of particles at the wall, e.g. LPT-DNS by Wang & Squires (1996), could not reproduce the experimental data of very dilute flow, e.g. the case of 2 % mass flow ratio by Kulick et al., (1994), with reasonable accuracy.

Tanaka et al. (1997) simulated a channel flow at $Re_\tau = 644$ laden with 70 μm copper particles, i.e. the flow with the most inertial particles used in the experiment by Kulick et al. (1994), and found that inter-particle collisions have a strong influence on the particle velocity statistics even at low mass flow ratio, Z, of 20 %. The RMS levels of wall-normal particle velocity fluctuations, v^p_{rms}, in a simulation with inter-particle collisions were computed to be almost twice as large as the case without collisions. Later, Fukagata et al. (1999) found that inter-particle collisions have considerable effects at even lower mass flow ratio, $Z = 2$ %.

For the last case, i.e. $Z = 2$ %, Fukagata et al. (2001) could reproduce the anomalous behavior observed in the experiment by Kulick et al. (1994), such as the large values of v^p_{rms} and the bimodal probability distribution function (PDF) of streamwise particle velocity at $y^+ = 12$ plane, by using rather artificial boundary conditions which suppress the re-entrainment of particles. The reason for the improvement was clearly illustrated by the statistics of the collided particles. The re-distribution of momentum components due to collisions among particles accumulated in the near-wall region caused the increase of v^p_{rms}. Shortcoming of their simulation, however, was that the excessive accumulation of particles in the near-wall region caused new discrepancies such as very low mean velocity in the vicinity of the wall and high streamwise RMS velocity, u^p_{rms}, in the bulk region.

A possible mechanism for the re-distribution of momentum components of particles without excessive accumulation in the vicinity of the wall may be collisions with rough walls. Such roughness on the walls is known to be essential for simulations of gas-particle horizontal channel flows in order to obtain realistic spatial distribution of particles (Tsuji, et al, 1985). Wall roughness should exist in experimental setups or real configurations regardless of the flow orientation, whether horizontal or vertical, though, it has usually been neglected in the LPT simulations of vertical channel flows.

The objective of the present study is therefore to examine the momentum re-distribution effects by the small roughness on the walls which will replace those by accumulation and collisions of particles in the vicinity of the wall. For that purpose, LPT-LES is performed taking into account a modeled wall roughness and the statistics of particles are investigated for several magnitudes of roughness.

METHODOLOGY

An overview of LPT-LES

The turbulent channel flow was simulated using LES and the particles were tracked individually.

The governing equations for the fluid are filtered continuity and Navier-Stokes equations. The SGS viscosity was modeled by an anisotropic version of the Smagorinsky model (Zahrai et al., 1995). The PSI-CELL model (Crowe et al, 1977) was used to evaluate the additional force term from due to the presence of particles.

The motion of individual particle was computed by integrating the particle equation of motion,

$$\frac{d\vec{u}^p}{dt} = \frac{1}{\tau_p}(1+0.15Re_p^{0.687})(\vec{u}^f - \vec{u}^p) + \vec{g}\,, \qquad (1)$$

where $\vec{u}^p$ and $\vec{u}^f$ are the velocities of the particle and the fluid, respectively. τ_p is the Stokes relaxation time. Re_p is the particle Reynolds number. $\vec{g}$ denotes the gravitational force. Inter-particle collisions were computed directly from the trajectories of particles. Perfectly elastic collisions were assumed and friction and rotation were neglected.

For the detailed procedure of the present LPT-LES including the inter-particle collisions, readers are referred to Fukagata et al. (2001).

The model for wall roughness

The wall roughness was modeled using the virtual wall model (Tsuji et al., 1985). This model assumes that the roughness height is negligible but the wall is inclined by an angle of α, as shown in Figure 1. The velocity of a particle after rebounce is then computed using a standard wall-particle impact model applied for the coordinate of the virtual wall, i.e. primed coordinate in Figure 1.

From the information obtained in the previous simulations and experiments, inertial particles are most likely to have small wall-normal velocity before impact such that the condition for the sliding collision (e.g. Crowe et al., 1998),

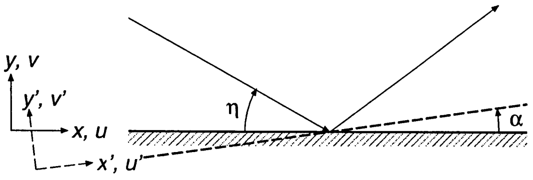

Figure 1: Virtual wall model (Tsuji et al. 1985; 1987).

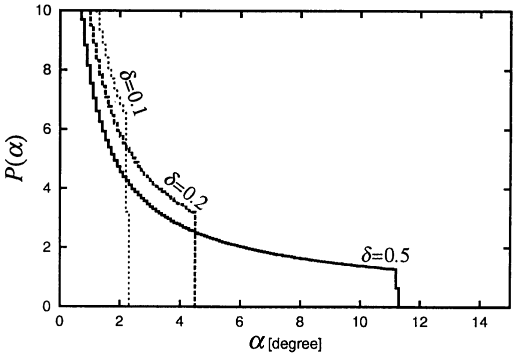

Figure 2: Simulated distributions of the roughness angle, α, for an impact angle, η = 2.5°.

$$-\frac{2}{7\,f(r+1)} < \frac{v^p}{|\vec{u}^p|} < 0\,, \qquad (2)$$

is satisfied. Here, r is the coefficient of restitution, f is the coefficient of friction. The velocity increment after the sliding collision is given by

$$\left\{\begin{array}{lcl} \Delta u^{p\prime} & = & \varepsilon_x^\prime\, f\,(r+1)\,v^{p\prime}\,; \\ \Delta v^{p\prime} & = & -(1+r)\,v^{p\prime}\,; \\ \Delta w^{p\prime} & = & \varepsilon_z^\prime\, f\,(r+1)\,v^{p\prime}\,. \end{array}\right. \qquad (3)$$

where $\varepsilon_x^\prime$ and $\varepsilon_z^\prime$ are the velocity fraction in the plane parallel to the virtual wall, i.e. $\varepsilon_x^\prime = |u^{p\prime}|/\sqrt{(u^{p\prime})^2+(w^{p\prime})^2}$ and $\varepsilon_z^\prime = |w^{p\prime}|/\sqrt{(u^{p\prime})^2+(w^{p\prime})^2}$.

The angle of the wall, α, was modeled (Tsuji et al., 1987) using a random number, R, as

$$\alpha = \left\{\begin{array}{ll} c\,R^k\,\delta(\beta-\eta) & \text{if } \eta < \beta\,; \\ 0 & \text{otherwise;} \end{array}\right. \qquad (4)$$

where η is the impact angle, $\beta = 7°$, $c = 5$ and $k = 4$ are the model parameters proposed by Tsuji et al. (1987). One can also express this model as the probability distribution function of α, which reads,

$$P(\alpha) = \left\{\begin{array}{ll} \frac{[c\delta(\beta-\eta)]^{-\frac{1}{k}}}{k}\,\alpha^{(\frac{1}{k}-1)} & \text{for } 0 < \alpha < c\delta(\beta-\eta)\,; \\ 0 & \text{otherwise.} \end{array}\right. \qquad (5)$$

In the original model by Tsuji et al. (1987) who studied horizontal flows, δ was empirically obtained as a function of Froude number, $Fr = \bar{u}/\sqrt{gh}$ where $\bar{u}$ is the mean fluid velocity and h is the channel height, as

$$\delta = \frac{2.3}{Fr} - \frac{91}{Fr^2} + \frac{1231}{Fr^3}\,. \qquad (6)$$

In the present study, however, δ was treated as a parameter because a relation relevant for vertical channel flows is not available. As the value of δ, several points between 0 (no roughness) to 0.5 were used. The simulated probability distribution function of the roughness angle is shown in Figure 2. The maximum roughness angle assumed here is smaller than typical value ($\alpha \simeq 17°$) of the polished steel plate experimentally examined by Frank et al. (1993).

Recently, a more sophisticated model for the wall roughness was proposed by Sommerfeld and Huber (1999). In their model, roughness was accounted for all impact angles, η. They derived theoretically the effective probability distribution function of α as [1]

$$P(\alpha) = \frac{1}{\sqrt{2\pi\Delta\alpha^2}} \exp\left(-\frac{\alpha^2}{2\Delta\alpha^2}\right) \frac{\sin(\eta+\alpha)}{\sin\eta}. \quad (7)$$

The model was validated by comparisons between experiments and simulations using six parameters including those concerning to the variations of the coefficients of restitution and friction, in addition to $\Delta\alpha$. The parameters relevant for various combination of the material of particles and walls and the size of particles were presented in their paper, though, those relevant for the present cases have not been reported. Therefore use of this model will be left for the future work.

RESULTS

Fluid statistics

Computations for the single phase turbulent channel flow were done using two different domain sizes and mesh systems (Cases A and B) as shown in Table 1. The geometry of the channel is shown in Figure 3. The Reynolds number of fluid flow based on the shear velocity and the half of channel width, $Re_\tau = u_\tau\delta/\nu$, was set to 644, which is the same as that in the experiment by the Kulick et al. (1994).

In Case A, the domain size may be too small especially in the streamwise direction and the mesh spacing in y direction in the center of channel, $\Delta y^+_{max} = 109.7$, is likely to be coarse as a large eddy simulation. However, Figures 4 and 5 indicate that the mean velocity and the RMS levels of velocity fluctuations of fluid can be computed with reasonable accuracy in Case A as compared to those in Case B and the experimental data by Kulick et al. (1994). Therefore the domain size and mesh system of Case A was used for the following simulations in order to save the computational cost. Use of coarser mesh can also be justified by the fact that the particles with very large inertia are less sensitive to the smaller structure of the flow.

The influence of the presence of particles to the fluid statistics were very small for the cases studied here. Therefore only curves of the undisturbed fluid are shown in the following figures on the particle statistics.

Effects of wall roughness on 70 μm copper particles

A flow of air laden with 70 μm copper particles was studied using various values of the model parameter, δ. The density ratio of particle to fluid was 7184 resulting in the Stokes relaxation time in wall unit, τ_p^+, about 2000.

Totally 1600 particles were tracked such that the mass flow ratio becomes about 2 %. Initially, particles were homogeneously distributed in whole channel and the particle velocities were set to the local fluid velocities. The statistics were

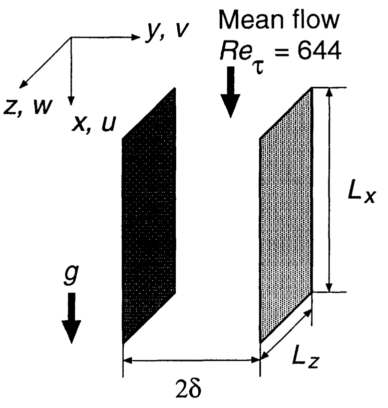

Figure 3: Computational domain.

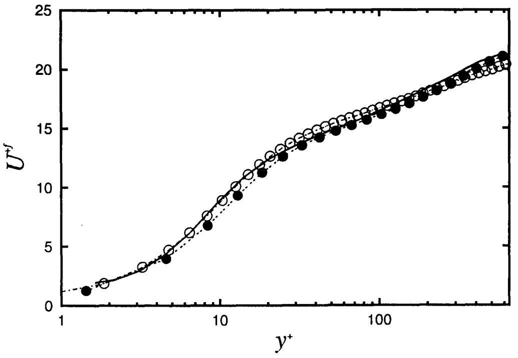

Figure 4: Mean velocity of the undisturbed flow at $Re_\tau = 644$. $\cdots\bullet\cdots$, Case A; $-\circ-$, Case B; ———, experiment by Kulick et al. (1994).

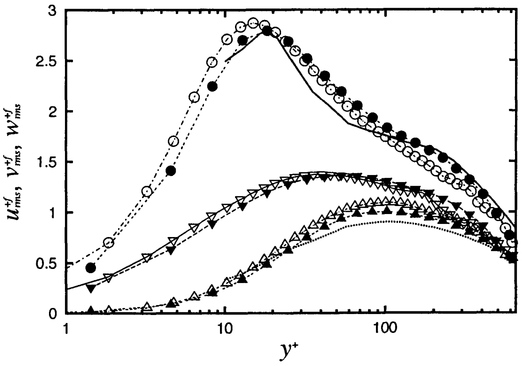

Figure 5: RMS levels of the undisturbed flow at $Re_\tau = 644$. $\cdots\bullet\cdots$, u^{+f}_{rms}; $\cdots\blacktriangle\cdots$, v^{+f}_{rms}; $\cdots\blacktriangledown\cdots$, w^{+f}_{rms}; Case A. $\cdots\circ\cdots$, u^{+f}_{rms}; $\cdots\triangle\cdots$, v^{+f}_{rms}; $\cdots\nabla\cdots$, w^{+f}_{rms}; Case B. ———, u^{+f}_{rms}; - - - - -, v^{+f}_{rms}; experiment by Kulick et al. (1994).

Table 1: Size of computational domain and mesh.

Case	L_x	L_z	N_x	N_y	N_z	Δx^+	Δy^+_{min}	Δy^+_{max}	Δz^+
A	$\pi\delta$	$0.5\pi\delta$	32	42	96	63.2	2.9	109.7	10.5
B	$2\pi\delta$	$\pi\delta$	64	84	192	63.2	1.2	59.6	10.5

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[1] The symbols are changed from the original one in order to be consistent with Figure 1.

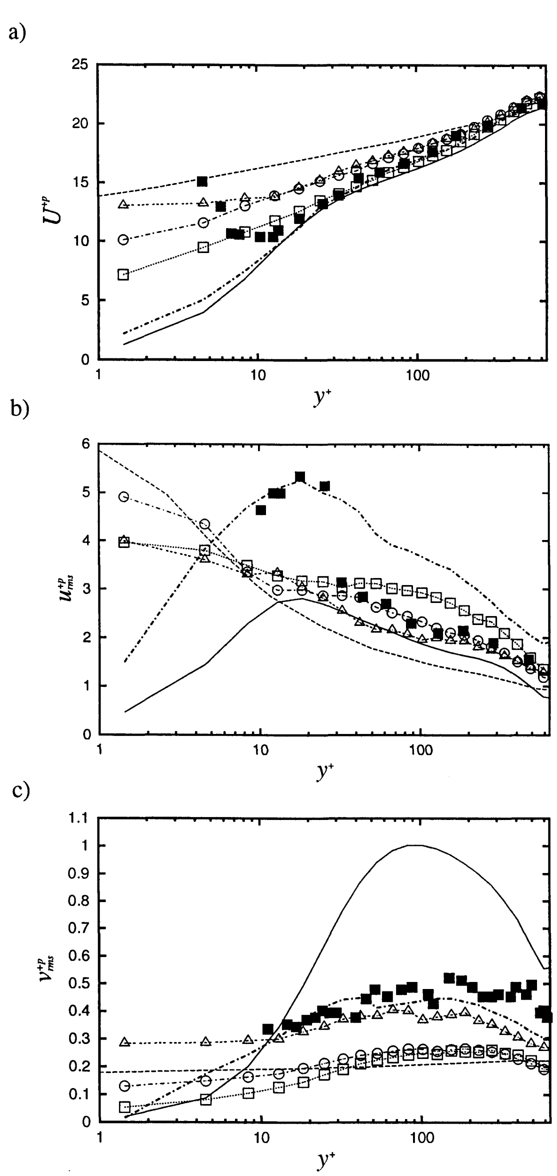

Figure 6: Influences of the parameter, δ, on the statistics of 70 μm copper particles in a turbulent channel flow at $Re_\tau = 644$, at 2 % mass ratio. Restitution coefficient, $r = 0.2$. a) mean velocity, b) RMS level of streamwise velocity, c) RMS level of wall-normal velocity. Present study: $\cdots\Box\cdots$, $\delta = 0$ (no roughness); – - ○ - –, $\delta = 0.2$; - -△– -, $\delta = 0.5$. ■, experimental data (Kulick et al., 1994); — — —, one-way coupling LPT-LES with perfectly elastic bounce at walls (Wang & Squires, 1996), ; – - –, four-way coupling LPT-LES with zero restitution coefficient and wall potential. (Fukagata et al., 2001); ——, fluid.

accumulated after the flow had fully developed. The development of the flow was judged by monitoring the Eulerian momentum balance (Fukagata et al., 1998).

Figure 6 shows the mean and RMS velocities of particles for various values of roughness parameter, δ. The restitution coefficient and the friction coefficient were fixed to $r = 0.2$ and $f = 0.4$, respectively. The superscript, $+$, denotes the

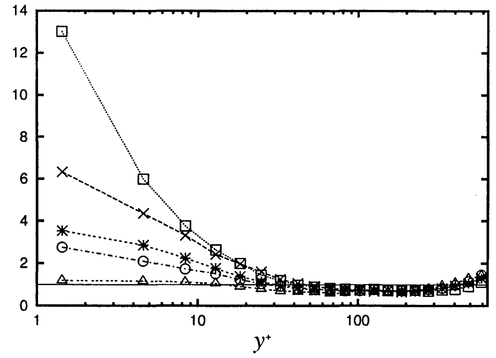

Figure 7: Particle number density profiles. $\cdots\Box\cdots$, $\delta = 0$ (no roughness); – - × - –, $\delta = 0.02$; - -∗– -, $\delta = 0.05$; – - ○ - –, $\delta = 0.2$; - -△– -, $\delta = 0.5$.

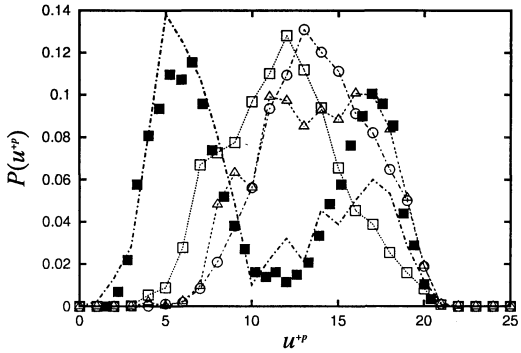

Figure 8: PDF of streamwise particle velocity at $y^+ = 12$. Captions are the same as those in Figure 4.

variables in wall units.

The most clear change was observed in the values of v^{+p}_{rms}. They increased with δ due to the momentum re-distribution by the collisions with rough walls, similarly to that by inter-particle collisions. The increase of v^{+p}_{rms} in the whole channel by the local phenomena at the wall can be explained by the long relaxation time of the particles, $\tau_p^+ \simeq 2000$. Namely, even the particles in the center of the channel *remember* the collisions with walls. In the case with $\delta = 0.5$, the values of v^+_{rms} are comparable to those of the experimental data by Kulick et al. (1994)

The mean particle velocity increased with δ, especially in the vicinity of the wall. It might be unexpected from a viewpoint of particle-wall collision itself, because the drop of streamwise velocity at impact with a rough wall increases as the magnitude of roughness increases. This observation can be explained rather by the global behavior of particles. The wall-normal velocity may take larger values due to the momentum re-distribution effect mentioned above. Faster re-entrainment from the viscous sublayer due to such large wall-normal velocity leads to faster recovery of the streamwise velocity.

The RMS values of streamwise particle velocity, u^{+p}_{rms}, were less changed by the presence of wall roughness, It should be noted that in the bulk region, say around $y^+ = 100$, u^{+p}_{rms} decreased while v^{+p}_{rms} increased as the increase of δ. This is contrary to the previous study (Fukagata et al., 2001) where both u^{+p}_{rms} and v^{+p}_{rms} increased as the enhancement of the accumulation of particles in the near-wall region.

Figure 7 depicts the change of particle number density profile for the studied roughness parameters, δ. Without roughness, the particles tend to accumulate in the vicinity of the wall due to the turbophoresis (Reeks, 1983) and also due to lack of re-dispersion mechanism except for inter-particle collisions. As the increase of the roughness parameter, the accumulation of particles in the vicinity of the wall was weakened. Eventually at $\delta = 0.5$, the number density became almost flat.

From the information above, one can conclude that the wall roughness works to enhance the transverse mixing of particles while less changing the structure of the streamwise velocity components. This was also confirmed by the PDF of streamwise particle velocity at $y^+ = 12$ plane shown in Figure 8. The PDFs were similar in all cases and the bimodal profile observed in the experiment (Kulick et al, 1994) and also in the previous simulation was not reproduced.

It is worth noting that the behavior of particles in the case where the closest statistics to the experimental data are obtained, i.e. fast re-entrainment from the viscous sublayer, is quite contrary to the desirable behavior proposed in the previous study (Fukagata et al., 2001). Therefore, a possible way to achieve better agreement with the experimental data may be to include both mechanisms: a) accumulation of particles in the vicinity of the wall; b) re-dispersion due to wall roughness. The former mechanism will work to generate the bimodality of the streamwise velocity, as demonstrated in the previous study; while the latter will increase v^p_{rms} and suppress the excessive u^{+p}_{rms} in the bulk region, as observed in the present study.

Computations were performed for other combination of coefficients of restitution, r, and friction, f. The results are summarized in Figure 7. It was observed that v^{+p}_{rms} in the bulk flow was less sensitive to the value of r and it increased as the increase of roughness parameter, δ. The local minimum around $\delta = 0.05$ for $r = 0.2$ and $f = 0.4$ may be explained as the followings. The momentum re-distribution effect by wall roughness increases as the increase of δ; while that by inter-particle collisions decreases as the increase of δ due to the rapid decrease of the particle number density in the vicinity of the wall. It was also observed that the streamwise velocity and the particle number density near the wall largely depended on r and f.

Effects of wall roughness on 50 μm glass particles

The study was continued for less inertial particles, i.e. 50 μm glass particles. The density ratio of particle to fluid was 2040, resulting in the Stokes relaxation time in wall unit, τ^+_p, about 280. The coefficients of restitution and friction were fixed to $r = 0.2$ and $f = 0.4$, respectively. Totally 16000 particles were tracked such that the mass flow ratio becomes about 2 %.

Only the summary of results are presented in Figure 10. Similarly to the case of 70 μm copper particles, decrease of

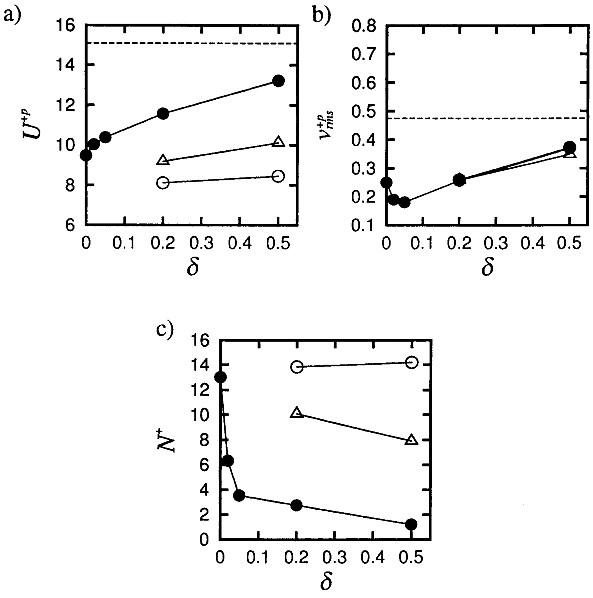

Figure 9: Influences of the parameter, δ, in other coefficients of restitution, r, and friction, f. 70 μm copper particles. a) mean velocity around $y^+ = 4.5$; b) RMS level of wall-normal velocity around $y^+ = 100$. c) particle number density around $y^+ = 1.4$. -•-, $r = 0.2$, $f = 0.4$; -○-, $r = 0.02$, $f = 0.4$; -△-, $r = 0.2$, $f = 0.8$; - - - -, the value in the experiment by Kulick et al. (1994).

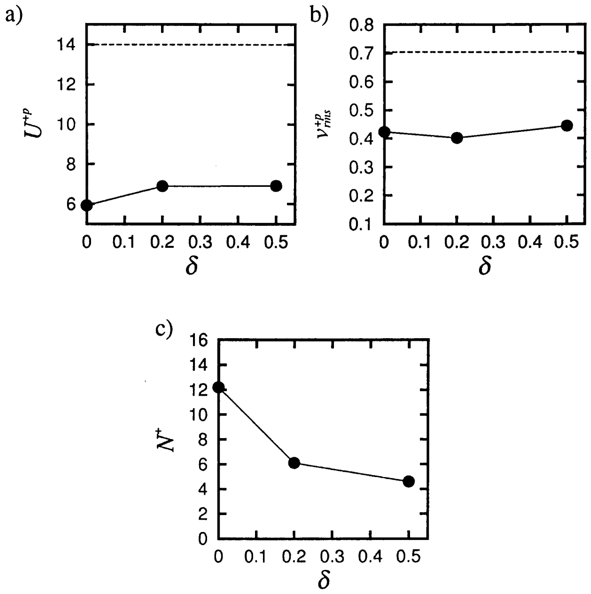

Figure 10: Summary of the results for 50 μm glass particles. a) mean velocity around $y^+ = 4.5$; b) RMS level of wall-normal velocity around $y^+ = 100$. c) particle number density around $y^+ = 1.4$. - - - -, the value in the experiment by Kulick et al. (1994). (U^{+p} around $y^+ = 4.5$ is not available in the experiment. Since the profile is nearly flat in this region, U^{+p} around $y^+ = 7.6$ is drawn instead.)

particle number density was observed in the vicinity of the wall by the introduction of wall roughness. However, the mean velocity near the wall and the RMS of wall-normal velocity fluctuation in the bulk flow were less influenced. They were still much lower values than those in the experiment. The only little change in the v_{rms}^{+p} in the bulk may be attributed to the shorter relaxation time of particles.

Simulations were done for only limited number of parameters, though, the discrepancy between simulations and the experiment in the case of 50 μm glass particles seem not to be explained by the effects due to wall roughness or inter-particle collisions which occur at or in the vicinity of walls.

CONCLUSIONS

Simulations of dilute gas-particle turbulent channel flow were performed. Among the possible causes for the discrepancies between the experiment and simulations performed in the past, effects of wall-roughness were studied.

In the case with 70 μm copper particles, even small amount of wall-roughness had considerable influences on the particle statistics. Simultaneous agreements of u_{rms}^{p} and v_{rms}^{p} with those of experimental data could not be satisfied in the previous simulation, though, this discrepancy was cleared in the present study owing to the influence of wall-roughness which especially works for increasing the wall-normal velocity fluctuations.

For better agreement with the experimental data, one should use more detailed model for the wall-roughness including the precise distribution of effective roughness, variations of the coefficients of restitution, r and friction, f, dependent on the impact angle or velocity, yet not known for the materials of particles and wall studied here. One may also have to consider some combined effects of the wall-roughness studied here and the attraction of particles toward the wall, e.g. by electrical potential.

The effects of wall-roughness was smaller in the case with 50 μm glass particles and modification in the statistics was found only in the vicinity of the wall. This may be due to the shorter relaxation time of the particles. There are still large discrepancies between the simulation and the experimental data, though, those could not be explained by the present study.

A final conclusion could be made. The behavior of inertial particles in a wall bounded turbulent flow is highly complicated and sensitive to various effects including the wall-roughness studied in the present work. Its prediction is far beyond the applicability of the simple one-way, two-way or even four-way coupling LPT simulations which may give accurate results for unbounded flows. At least, correct modeling of the wall-particle collisions is required for accurate prediction, especially for dilute flows where the effects of inter-particle collisions are not that strong.

ACKNOWLEDGMENT

The first author (KF) acknowledges the financial support by the Ministry of Education, Culture, Sports, Science and Technology, Japan, through the project, *Smart Control of Turbulence* (Study for open and integrated research program), under which part of this work was done.

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