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LES OF GAS-PARTICLE TURBULENT CHANNEL FLOW

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ABSTRACT

Numerical simulations with two-way coupling were performed for downward particle laden turbulent flows in a vertical channel. Fluid motion was calculated by using LES with the same models as in single phase flows and the motion of individual particles by the Lagrangian method. Particle-particle collision was taken into consideration. It was found that the effects of particle-particle collision on particle diffusion is large even at low particle volume fraction of the order O(10^{-4}). Some results were compared with measurements by Kulick et al. (1994). The present simulation showed that fluid turbulence is modified by particles but quantitatively it did not get a good agreement with the measurement.

INTRODUCTION

LES and DNS which have been widely used for analysis of turbulent flows in single phase is now attracting attention of people engaged in multiphase flows. Like the single phase flows, other turbulence models such as Reynolds stress model and $k-\varepsilon$ model also are popular in multiphase flows. The advantageous point of DNS is that these methods need less assumptions. However there are several problems ahead of us to apply these method to multiphase flows. It is difficult even for modern super computers to solve instantaneous turbulent fields between moving individual particles in the presence of a great number of particles. Therefore, various simplification models are proposed to simplify the treatment of problems. For instance, a particle is regarded as a point with no volume. Until early 1990's, DNS calculations of fluid particle flows were made based on one-way coupling, but now two-way coupling calculations are quite common. Still, calculations based on DNS are limited to relatively simple cases such as isotropic turbulence fields and dilute phase flows where particle-particle collision is neglected. However comparing the present days with the days when DNS was not applied to multiphase flows, much progress has been done by DNS application. Several groups are active in this field, like Elghobashi, Squires & Eaton and Wang & Maxey. For more details of references, see reviews by Crowe et al. (1996).

We have been interested in dense phase flows where particle-particle interaction has dominant effects on flows. In our previous work of channel flows (Tanaka & Tsuji (1991), Yonemura et al.(1993), Tanaka et al.(1995), Tanaka et al.(1996)) we used another simplification; gas was assumed inviscid except for considering fluid drag. Under this assumption satisfactory results were obtained concerning the central part of channels. We succeeded in showing that particles form clusters by repeating particle-particle collision. It is clear that as long as we used inviscid gas assumption, we were not able to get reasonable results near the wall. When considering the power of the present days super computers, DNS is not suitable for gas-solid channel flows because the range of Reynolds number is limited to values low compared with flows in practice. . Thus we decided to use LES. As an example of LES application to gas-particle flows, the work of Lavieville et al.(1995) should be cited. Particle-particle collision was taken into account in an isotropic turbulent field but the calculation was based on the one-way coupling.

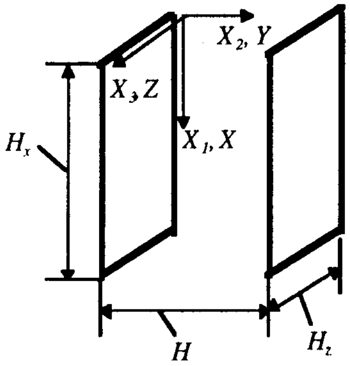

Fig. 1 Calculation region

EQUATION OF GAS MOTION

Fig 1 shows the calculation region of the present work. Periodic boundaries were adopted in the longitudinal and span-wise directions.

The Cartesian coordinate system was used. That is,

x or x_1: stream-wise (longitudinal) direction
y or x_2:transverse direction
z or x_3: span-wise direction

The filtered equations of continuity and momentum are as follows.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} = \frac{\partial}{\partial x_j}\left\{-u_i u_j - \delta_{ij} P + \nu_s\left(\frac{\partial u_i}{\partial u_j} + \frac{\partial u_j}{\partial u_i}\right)\right\} + \frac{\Delta p}{H_x}\delta_{i1} + f_{Pi} \tag{2}$$

where

$$P = \frac{p}{\rho} + \frac{\Delta p}{H_x} x_1 + \frac{1}{3} R_{kk},$$

$$\nu_s = \nu + \nu_{SGS}$$

The above formulation is basically the same as the one by Deardorff(1970), except for the last term f_{Pi} in the right hand side of Eq.(2). The last term represents the momentum exchange between particles and gas.

The SGS(Subgrid scale) Reynolds stress $R_{ij} (\equiv u_i' u_j')$ is given by

$$R_{ij} = \frac{1}{3}\delta_{ij} R_{kk} - \nu_{SGS}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

We used the Smagorinsky model as the eddy viscosity which is given as follows.

$$\nu_{SGS} = \left(C_s \Delta_s f_s\right)^2 \left|\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right| \tag{4}$$

where C_s is a non-dimensional empirical constant, Δ_s, filter scale and f_s, damping function. The filter scale Δ_s is defined by

$$\Delta_s \equiv \sqrt[3]{\Delta_1 \Delta_2 \Delta_3}$$

Concerning the SGS model, the same formulation and the same constants as in the single phase flow were used for the present gas-particle flows, because of lack of idea of modification due to the presence of particles .Therefore the following value which is preferred for single phase turbulent channel flows.

$$C_s = 0.1$$

The damping function is expressed as

$$f_s = 1 - \exp\frac{-x_2^+}{25}$$

x_2^+ is the non-dimensional distance from the wall defined by

$$x_2^+ = \frac{x_2 u_\tau}{\nu}$$

What modification is necessary for the SGS model in two-phase flows is open question. This problem should be studied in future work.

SOLUTION ALGORITHM

We used a staggered grid system and used the 2nd order accuracy central finite difference scheme for spatial difference. The velocity and pressure are determined by SMAC method. To solve the Poisson equation, we used the spectrum method which enables us to obtain solutions without iteration.

EQUATION OF PARTICLE MOTION

Concerning the particle motion in gas under the influence of gravity, equations are the same as in our previous papers (Tanaka and Tsuji, 1991). Also, the same equations as Tanaka and Tsuji(1991) were used concerning the relation of particle velocities before and after collision. In our previous papers following Tanaka and Tsuji (1991), we used successfully the DSMC method to find collision pairs (Yonemura et al.(1993), Tanaka et al. (1995), Tanaka et al.(1996)) but we did not use the DSMC method in this work. We used the deterministic method in the same way as Tanaka and Tsuji(1991).

The reason that we did not use the DSMC method in this work is as follows. In the present calculation, the mesh size inevitably became small near the wall to catch the turbulent eddies there. A pre-requisite condition of using the DSMC method is that a sufficient number of particles exist in the cell. That condition was not satisfied in this calculation. If we increased particle loading, the number of particle could be large enough to apply the DSMC method. However, under the assumption that the same models and the same constants as the single phase flows are applied concerning the SGS model, calculated results for cases of high loading mean nothing though the calculation itself would be possible.

CALCULATION CONDITIONS

As described in the previous sections, we calculated flow in a downward vertical channel with periodical boundaries in the x and z directions . The width of the channel H=0.04 m. The length between x-boundaries is $2.2H$ and the length between z-boundaries is $0.74\ H$. The field is divided into 48 segments in the y-direction, 64 segments in the x-direction and 64 segments in the z-direction. Table 1 shows conditions of particles.

Table 1 Conditions of particle

Material	Glass	Copper	
Density ρ_p $\left[kg/m^3\right]$	2500	8800	
Diameter D_p $[\mu m]$	50	70	
Terminal velocity v_t $[m/s]$	0.18	0.93	
Solid volume fraction $[\times 10^{-4}]$	0.96	0.27	1.4
Mass ratio Z	0.2	0.2	1.0
Loading ratio ϕ	0.25	0.26	1.3
Number of particles	154,214	15889	79445
Coefficient of restitution	0.95		
Coefficient of friction	0.3		

The physical properties of the above particles and the flow conditions are the same as in the experiments by Kulick et al. (1994).

The initial conditions are as follows. The initial velocity of the x-component is the sum of the mean value based on the logarithmic law and fluctuation given by random number. The velocities in y-and z-directions have only fluctuating components which are given by random numbers. The initial pressure fluctuation is assumed to be 0. The computer used in this work was NEC SX-3R.

RESULTS

We were interested in the effects of inter-particle collision on the calculated results, and thus the following figures include results with and without considering inter-particle collision.

Profiles of particle number density are shown in Fig.2 where the results are normalized by the average value. Z means the mass ratio of solid to gas. In the figure, the results with and without considering the particle-particle collision are compared. It is found that the particle-particle collision clearly influence the results even though the particle concentration is very low. When the collision is neglected, particle number density becomes extremely high near the wall. Such high density disappears due to the inter-particle collision. The particle-particle collision has been often neglected for such a condition of low particle concentration. We (Tanaka and Tsuji, 1991) have already pointed out that the particle-particle collision largely affects particle dispersion even for the particle volume fraction of the order of $O(10^{-4})$. However those results in our previous work were obtained under the assumption of inviscid gas. Thus, more precise calculation has been needed to get some conclusion concerning the phenomena near the wall From the present results we reconfirm the importance of the particle-particle collision in the Lagrangian method.

Figure 3 and 4 show rms values of particle streamwise fluctuation velocity. The results of corresponding value of gas are also plotted. The effects of the particle-particle collision are clearly observed in each figure. The present calculation well predicts the profile of particle streamwise fluctuation velocity except for the central region for copper particles.

Figure 5 shows the profiles of particle transverse fluctuation

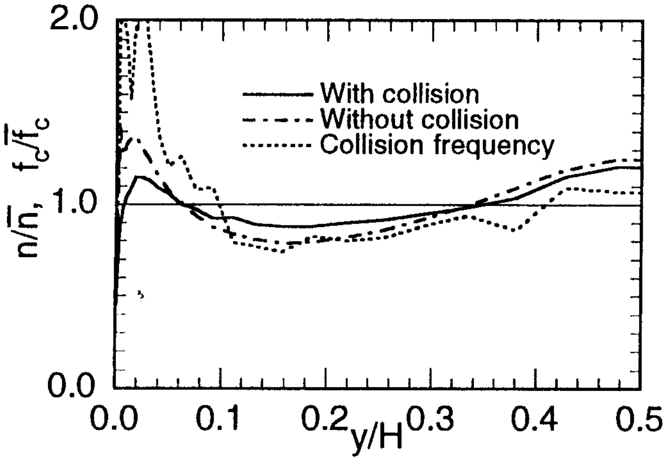

Figure 2 Profile of particle number density (copper, Z=0.2)

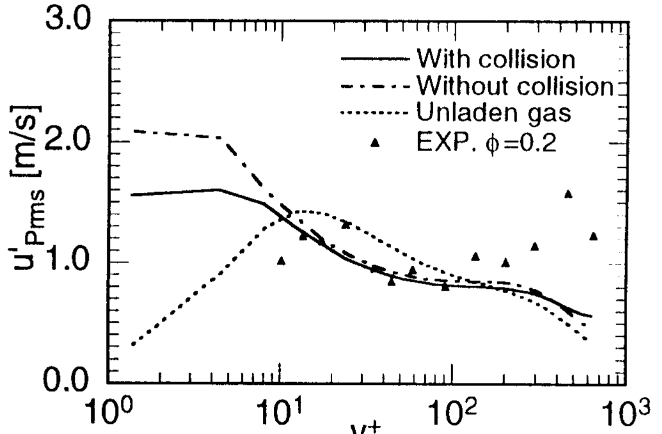

Figure 3 Profile of particle streamwise fluctuation velocity (copper, Z=0.2)

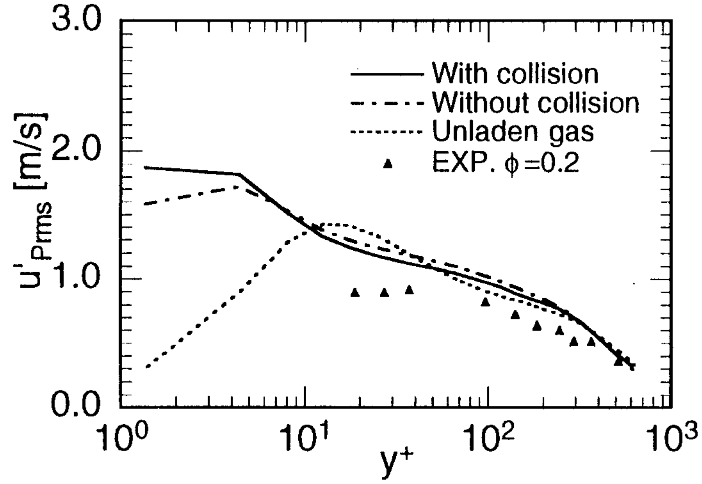

Figure 4 Profile of particle streamwise fluctuation velocity (glass, Z=0.2)

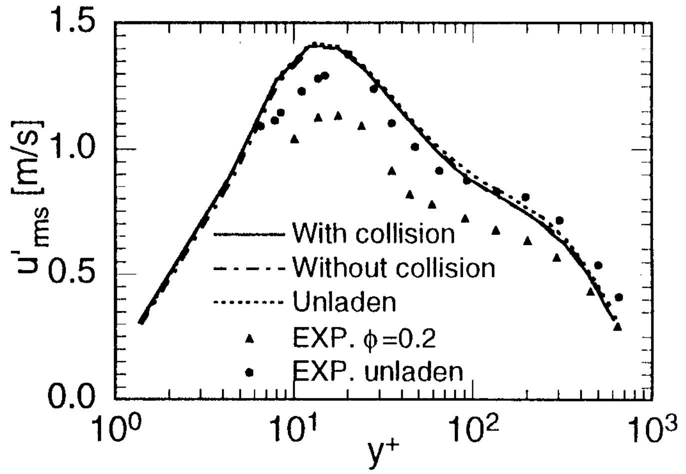

Figure 6 Profile of streamwise fluctuation velocity of gas (copper, Z=0.2)

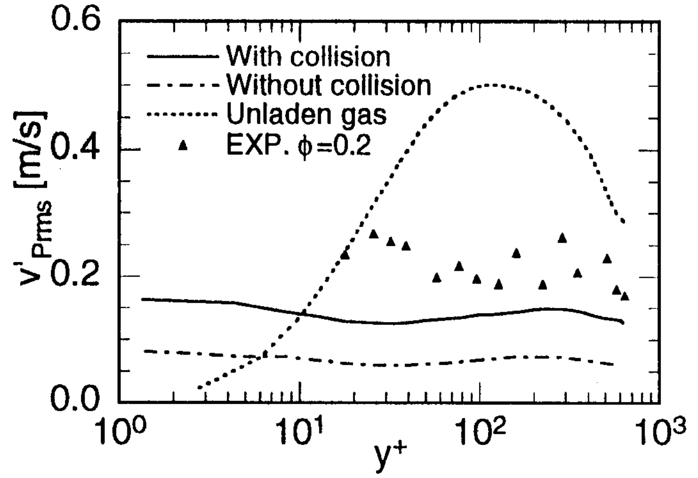

Figure 5 Profile of particle transverse fluctuation velocity (copper, Z=0.2)

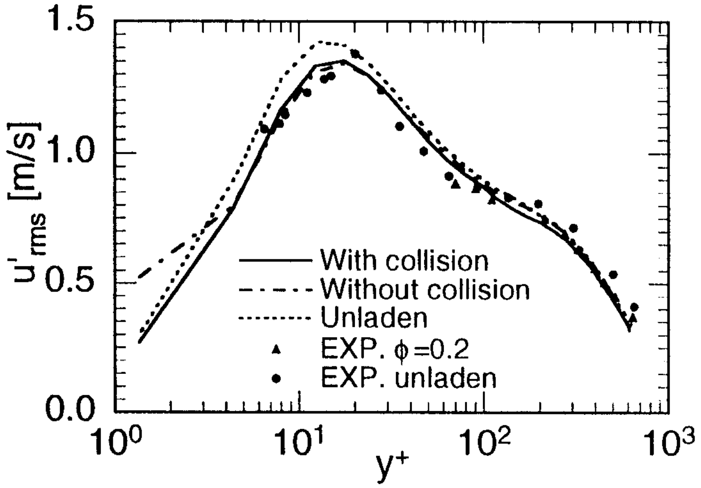

Figure 7 Profile of streamwise fluctuation velocity of gas (glass, Z=0.2)

velocity. The profiles are nearly uniform in the cross section. Without collision the predicted fluctuation velocity is remarkably smaller than the experiment. Though the predicted fluctuation velocity is still smaller than the experiment, the agreement with the experiment is fairly good.

Figure 6 and 7 show the profiles of streamwise fluctuation velocity of gas. Although the experimental results clearly show turbulence reduction due to particles, the present results do not show it clearly. Slightly such tendency is observed in the results of glass particles (Figure 7).

Finally, the relation between the streak structure and particle number density near the wall are shown. High speed and low speed streaks are shown in Figure 8, where black parts correspond to the high speed streak (HSS) and gray parts to the low speed streak (LSS). The flow direction is from left to right. Fig. 9 shows contours of particle number density obtained at the same distance from the wall. The black parts in Figure 9 correspond to high density region and gray parts to low density region. When comparing Figs. 8 and 9 carefully, high density areas tend to correspond to LSS and vice versa. See LSS A, B and C in Figure 8. This result is similar to the results shown by Rouson and Eaton (1994) and Wang and Squires (1996).

CONCLUSIONS

Instantaneous motion of gas and particles in a downward vertical channel has been solved with LES considering interaction between gas and particle (two-way coupling) and interaction between particles (inter-particle collision). Any modification for the presence of particles was not made concerning the SGS model.

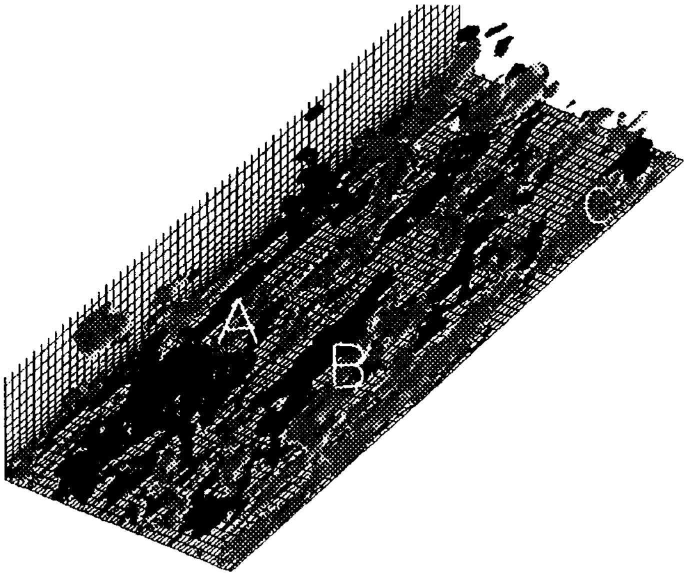

Figure 8 Streak structure (black:HSS, gray:LSS)

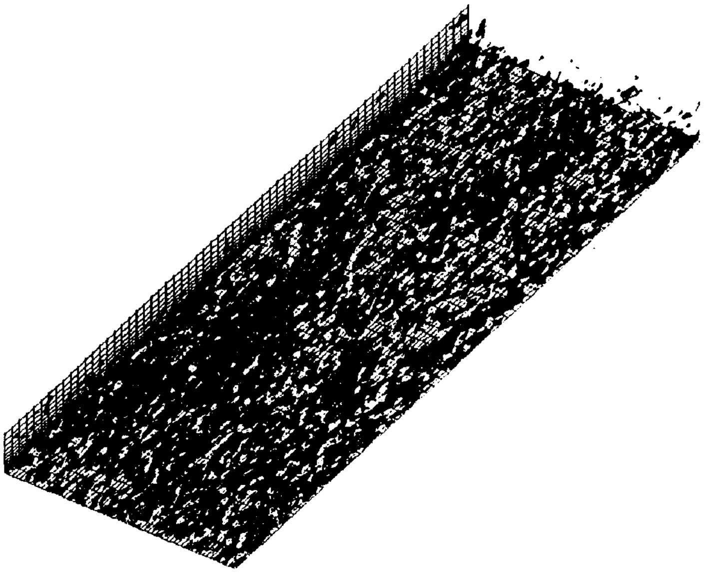

Figure 9 Distribution of high particle concentration

The calculation was performed under the condition of dilute phase (solid volume fraction = $O(10^{-4})$)

Effects of inter-particle collision on particle motion is clearly observed even for the above low concentrations. i.e.,

1. Particle concentration becomes flatter
2. Particle turbulence increases

Turbulence reduction is slightly observed in the present calculation but its degree is extremely small compared with measured results.

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