Structure of Particle Clusters Formed in Gas-Solid flows

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Abstract: Characteristics of spatial structure of particle clusters are investigated by using the flow field data obtained from three-dimensional numerical simulations. Eulerian/Lagrangian approach with two-way coupling is applied and individual particle-particle collisions are taken into account by using the hard-sphere model. More than 16 million particles are traced in the maximum case. The results show that the cluster is consisted from the multiple-spatial scale components while the low wave-number, hence the large-scale structure, is dominant. Three-dimensional structure reconstructed from the low-pass filtered data enables us to investigate the essential dynamics of particle clusters in detail.

Keywords: Particle Cluster, Multi-Scale Structure, Self-Organization, Eulerian/Lagrangian Method, Structure Extraction

1. INTRODUCTION

It is well-known that meso-scale structures of solid particles are formed in a wide range of gas-solid flows. In moderately dense systems such as circulated fluidized bed and pneumatic conveyer, particles tend to make clusters. Clustering particles have significant effects on the surrounding flows and enhance the transport performance of flows drastically. Thus, many studies on the clustering flow in risers of circulating fluidized beds (CFBs) have been performed, for example, see Horio & Kuroki [1] and Tsukada et al. [2].

In this paper, characteristics of spatial structure of clustering particles are investigated by using the flow field data obtained by three-dimensional numerical simulations [3]. Eulerian/Lagrangian approach with the two-way coupling is applied. Individual particle-particle collisions are taken into account by using the hard-sphere model. More than 16 million particles are traced in the maximum case. High/low-pass filters are used to investigate relations between the spatial scale component and structure. The three-dimensional structure of particle clusters is also investigated.

2. GOVERNING EQUATIONS AND NUMERICAL METHODS

2.1 Particle motion

Particles are assumed to be rigid spheres whose density and physical properties are uniform. The equation of translational motion of a particle is given by

$$m\frac{du_{pi}}{dt} = \frac{1}{2}C_D\rho_f A|u_i - u_{pi}|(u_i - u_{pi}) + mg\delta_{i1} \qquad (1)$$

where m is the mass of a particle, u_{pi} is the particle velocity, u_i is the gas velocity, g shows the gravity acceleration. For the drag coefficient C_D, the correlation by Schiller and Nauman is used.

The equation of rotational motion of a particle is also considered. The viscous dissipation of particle rotation relative to the local fluid rotation is considered.

The particle-particle collision effect is important for the cluster development. We adopted a deterministic method for the hard sphere model proposed by Tanaka and Tsuji [4].

2.2 Fluid flow

In this study, the cell size for fluid calculation is much larger than the particle diameter, hence, the fluid/particle momentum coupling is performed by using the point force model. The governing equations of the incompressible viscous flow are the equation of continuity and Navier-Stokes equation.

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (2)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\Delta p}{L_x}\delta_{i1} + F_{pi} \qquad (3)$$

where u_i and p are the fluid velocity and pressure, respectively. An adverse pressure gradient, $\Delta p/L_x$, which balances with the gravitational force acting on particles is applied to keep the steady state. F_{pi} represents the reactive force acting on the fluid from particles. This is given by the sum of fluid drag of all particles in a fluid computational cell. In this study, the solid volume fraction is not so high, hence, the effect of particles volume is neglected in the fluid calculation. These equations are discretized on a uniform staggered grid by the finite difference method. Second-ordered central difference and second-order Adams-Bashforth schemes are used for the spatial and temporal derivatives, respectively. SMAC method is used for the coupling between Eqs. (2), (3).

Table1: Physical properties

Gas density, ρ_f [kg/m^3]	1.205
Gas viscosity, ν [P_s]	1.809 x 10^5
Particle density, ρ_p [kg/m^3]	2470
Particle diameter, d_p [μm]	128
Coefficient of restitution, e_p	0.9
Coefficient of friction, μ_p	0.3

Table 2: Calculation parameters

Case	L_x [mm]	L_y, L_z [mm]	ϕ_v	N_p
A	128	32	2.1x10^{-3}	251,990
B	128	64	2.1x10^{-3}	1,007,961
C	128	128	2.1x10^{-3}	4,031,847
D	128	256	2.1x10^{-3}	16,127,388

3. Calculation Conditions

The physical properties of gas and solid particles are shown in Table 1. Fluid and particle are assumed to be air and glass, respectively. Parameters of all cases are show in Table 2. All cases are computed in a box with L_x [mm] x L_y [mm] x L_z [mm] sides. Triple-periodic boundary condition is used. We will have discussions on the effect of spanwise domain size, therefore, Cases B, C and D have cross-sections 2^2, 4^2, 8^2-times larger comparing to Case A, respectively. All cases have the same averaged particle volume loading. Hence, number of particles increases corresponding to the domain size. Case D, the largest case we computed, has more than 16 million particles in the flow domain. The gravity is working on the x-direction. Spatial increment is uniform for all directions and is set to Δx =1 [mm]. Temporal increment is set to $\Delta t = 1 \times 10^{-4}$ [s].

4. RESULTS AND DISCUSSION

4.1 Effect of domain size and spectrums

Effect of spanwise domain size on the spatial structure of particle clusters is examined. Fig. 1 shows the averaged power spectrum of spanwise SVF (Solid Volume Fraction). This figure shows that case D has enough spanwize box size to capture the cluster structure.

4.2 Structure extraction

As we see in Fig. 1, the spatial structure of particle distribution has the nature of multi-scale structure, and characteristic energy of SVF fluctuation is almost retained by the low wave-number components. It is intriguing to know the relation between the scale components and the spatial structure. Hence, we separated large and small spatial structure of particle concentration by applying the low/high pass filtering. Three kinds of cutoff wave number, k_{th} =100, 50, 20 [1/m], are examined. Spanwise results are shown in Fig. 2.

It is confirmed that low-pass filtered data retain a general feature of the cluster while detailed structures are eliminated. Degree of anisotropy is intensive for the low components comparing to the high components. This becomes more apparent in the case of a smaller cutoff value (k_{th} =20 [1/m]). By using the low pass filtering, we can extract the structure which is energetic and governing the flow.

Fig. 3 shows a three-dimensional spatial structure re-constructed from the low-pass filtered data ($k \leq 100$). The value of the SVF iso-surface is set to 0.003. Three-dimensional structure of particles clusters can be clearly observed in this figure. Without applying filter extraction, it is not easy to observe the cluster structure due to the existence of small scale components.

ACKNOWLEDGMENTS

This study is supported by the Japan Society for the Promotion of Science (Grand-in-Aid for Scientific Research 17560149). The third author also would like to thank Hosokawa Powder Technology Foundation for their financial support. All computations were performed on NEC SX-5 at Cybermedia Center, Osaka University.

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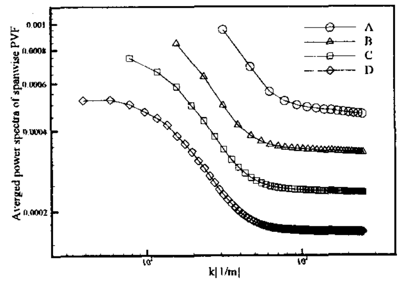

Fig. 1 Averaged spanwise SVF power spectrums.

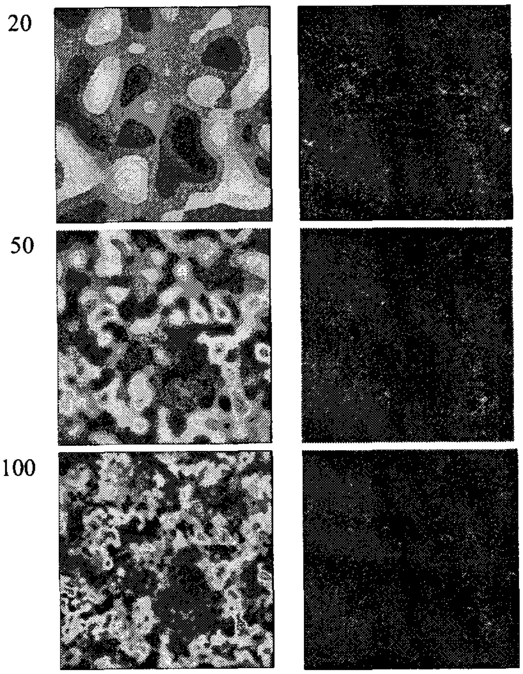

Fig. 2 Spanwise high/low wave-number components. (case D)

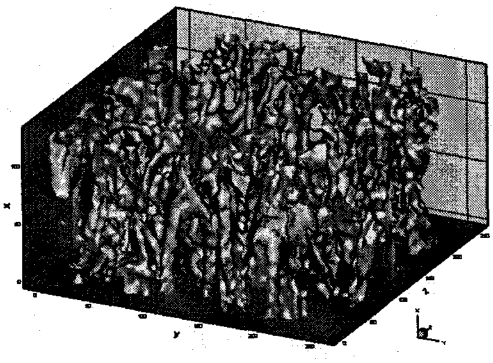

Fig. 3 3-D cluster structure re-constructed from the low-pass filtered data