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Study of cluster formation in dense two-phase flow using a multi-lattice deterministic model

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Abstract

To simulate cluster formation in dense two-phase flow, a multi-lattice deterministic trajectory (MLDT) model is developed. The actual inter-particle collision and particle motion are treated by a Lagrangian trajectory model with three sets of lattices to reduce computation time. Initially, the MLDT model is used to simulate dense gas-particle flow in a vertical channel for validation with available simulated and experimental data. Using the MLDT model, effects of particle properties and flow parameters on cluster formation are studied. It is shown that cluster formation is enhanced by the reduction of particle restitution coefficient and increase of original particle volume fraction.

Keywords: Cluster formation; Multi-lattice deterministic trajectory (MLDT) model; Dense two-phase flow

1. Introduction

In dense two-phase flow, inter-particle collisions occur frequently resulting in significant particle cluster formation. Interaction within the particle phase must be considered for numerical simulation of dense two-phase flow, in which proper modeling of particle motion and inter-particle collision is important.

With Lagrangian approach, the particle motion and inter-particle collisions are calculated for all the particles in the flow field. This trajectory model is based on the deterministic trajectory model, the stochastic trajectory model [1,2] and the improved stochastic separated flow model [3]. The drawback of such model is the great demand on computation time and memory for number of particles sufficiently large to represent a physical situation. It is therefore impractical when the number of particles is very large. To reduce the enormous computation time, collision probability theory is often used [4,5]. With this method, particles are replaced by sample particles and inter-particle collisions are replaced by dummy collisions of these sample particles. Particle positions and velocities are obtained randomly. However, many over-simplified assumptions are adopted in this method and quantitative analysis is not suitable. For example, the cluster patterns in circulating fluidized beds predicted by a discrete particle model are very different from the results predicted by a two-fluid model. As reported by Tsuji et al. [6], some results based on these assumptions are even qualitatively opposite.

In this paper, a multi-lattice deterministic trajectory (MLDT) model is developed to simulate dense two-phase flow. The actual inter-particle collision and particle motion are treated by a Lagrangian trajectory model, and multi-lattices are used to reduce the computation time. To verify the MLDT model, it is first used to simulate gas-particle upward flow in a vertical channel. Simulation results are compared with previous simulated and experimental data and reasonable agreement is observed. Using the MLDT model, effects of particle properties and flow parameters on cluster formation are studied for dense two-phase flow in a square domain with periodic boundary conditions. It is shown that reduction of particle restitution coefficient, increase of original particle volume fraction and increase of gas fluctuating velocity enhance cluster formation.

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2. Numerical approach

2.1. Particle motion

The equation of particle motion, neglecting higher order terms, is given by

$$\frac{d\vec{V}_p}{dt} = \vec{f_d} + \vec{f_c} + \vec{g}, \quad (1)$$

where $\vec{f_d}$ is the fluid force exerting on the particle, $\vec{f_c}$ is the contact force when particles collide, and $\vec{g}$ is the gravitational force.

For a single particle in the flow field, a term related to $\vec{f_d}$ is first introduced such that

$$\vec{f_s} = \frac{\vec{V_g} - \vec{V_p}}{\tau_{rp}/f}, \quad (2)$$

where τ_{rp} is the particle diffusion relaxation time and f is an empirical coefficient, given by

$$\tau_{rp} = \left(\rho_p d_p^2\right)/(18\mu) \quad (3)$$

and

$$f = 1 + 0.15Re_p^{0.687}. \quad (4)$$

In dense particle flow, the constraint of space between particles results in higher gas velocity and thus larger shearing stress. This in turn results in an increase of the drag force $\vec{f_d}$ when the particle volume fraction ε_p increases. Hence $\vec{f_d}$ is given by You et al. [7],

$$\vec{f_d} = \left(1 - \varepsilon_p\right)^{-3.65} \times \vec{f_s} \quad (5)$$

2.2. Inter-particle collision

For particle collision, only the contact force $\vec{f_c}$ is considered as it is by far the dominant force as compared with the fluid force and gravitational force. In the MLDT model, all the particles are assumed to be rigid spheres without rotation. In addition, only binary collision is assumed such that a particle does not collide with more than one particle in a single time step [8]. At each time step of the actual inter-particle collisions calculated by the model, a procedure is performed to decide whether a particle collides with another particle so that post-collision velocities and positions of the collision pairs are updated.

2.2.1. Collision determination

The collision between two particles is illustrated in Fig. 1. Particle A is assumed to be stationary while particle B has a relative velocity V_{ba}. When the two particles collide within a time step Δt, the following three criteria are assumed:

1. $AB < \mathrm{ds}$, where ds is a threshold value to determine neighbouring particles;
2. $\gamma < \angle ABC'$ where γ is the angle between vector $\vec{V}_{ba}$ and $\overrightarrow{BA}$ and C' locates the positions of the centre of the second particle where it just misses the first;

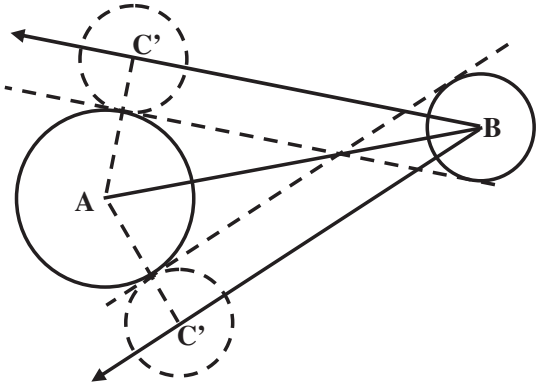

Fig. 1. Particle collision.

3. $t < \Delta t$, where t is the time from the beginning of the time step to the moment of contact.

Fig. 2 shows the actual positions of the two colliding particles, and hence t is given by

$$t = \frac{BC}{|\vec{V}_{ba}|}, \quad (6)$$

where BC can be obtained geometrically and $\vec{n}$ is the unit normal vector directed from the centre of particle A to that of the moving particle. After time t, positions of the two particles can be calculated by integrating the equations of motion.

2.2.2. Post-collision velocities

When the collision pairs are determined, post-collision velocities can be obtained by the impulse equation as

$$\vec{V_a} = \vec{V_a^0} - \frac{m_b}{m_a + m_b}(1+e)\left(\vec{n}\ \vec{G^0}\right)\vec{n}, \quad (7)$$

$$\vec{V_b} = \vec{V_b^0} + \frac{m_a}{m_a + m_b}(1+e)\left(\vec{n}\,\vec{G^0}\right)\vec{n}, \quad (8)$$

where the superscript (^{0}) refers to values before collision, $\vec{G}$ is the velocity of particle A relative to particle B, and e is the coefficient of restitution, defined as

$$\vec{G}\ \vec{n} = -e\left(\vec{G^0}\ \vec{n}\right). \quad (9)$$

2.2.3. Multi-lattices

With the usual trajectory model, most of the computing time is spent on determining the collisions for all pairs of particles in the entire flow field. However, a particle can only collide with particles in its vicinity. A lattice deterministic trajectory model (LDT) is introduced as shown in Fig. 3(a) where collisions of particles only occur for particles within the same lattice. Numerical simulation of dense gas-particle flow is carried out to investigate the LDT model. The computation domain is 30 mm × 30 mm with periodic boundary conditions, containing 10,000 particles with a diameter of 100 μm. During the simulation, mean gas velocities are kept at 1 m/s in the x-direction and zero in the y-direction. The fluctuating velocity components are distributed uniformly in both directions with a magnitude of ±0.5 m/s. With the LDT model, 25 × 25 lattices