INFLUENCE OF THE PRESENCE OF FINES ON THE FLUIDIZATION OF LARGE PARTICLES

Eivind HELLAND, René OCCELLI and Lounès TADRIST
Institut Univeristaire des Systèmes Thermiques Industriels
CNRS (UMR 6595) - Technopôle de Château Gombert
5, rue Enrico Fermi - 13453 Marseille Cedex 13
T: + 33-4 91 10 69 36 - F: + 33-4 91 10 69 69 - E: evin@iusti.univ-mrs.fr

In this paper we investigated numerically the influence of the presence of fines on the fluidization behaviour of large particles. The numerical simulation plays an important role in the prediction of the flow behaviour in fluidized beds [1, 2]. Both Eulerian and Lagrangian approaches can be used to describe the system. At present the Eulerian description for both the solids and gas phase is most developed, but interest in the mixed Eulerian-Lagrangian approach [3-4] is growing as computional capacity increases.

Numerical model

The Eulerian / Lagrangian method computes the Navier Stokes equation for the gas phase and the motion of invidual particles by the Newtonian equations of motion. For the gas phase, we write the equations of conservation of mass and momentum :

$$\frac{\partial(\varepsilon\rho_g)}{\partial t} + \nabla\cdot(\varepsilon\rho_g\vec{u}) = 0 \tag{1}$$

$$\frac{\partial(\varepsilon\rho_g\vec{u})}{\partial t} + \nabla\cdot(\varepsilon\rho_g\vec{u}\vec{u}) = -\varepsilon\nabla\cdot(p\bar{\bar{I}}) + \nabla\cdot\varepsilon\bar{\bar{\tau}}_g + \varepsilon\rho_g\vec{g} - \sum_{i=1}^{Np(V)}\vec{f}_{drag,i} \tag{2}$$

In discrete particle models for each individual particle an equation of motion is solved during the free flight phase :

$$m_i\frac{d\vec{v}_i}{dt} = m_i\vec{g} + \vec{F}_{drag} - V_p\nabla p \tag{3}$$

where m_i, v_i represent respectively the mass and velocity of the i^{th} particle and the right hand side the sum of the forces acting on the i^{th} particle; the first term is due to gravity, the second due to drag between the gas and solids phase and the third the pressure gradient force. The unsteady forces have been neglected due to the high solids to gas density ratio. The slip / rotation or Magnus lift force and the slip / shear or Saffman lift force have also been neglected due to the small particle diameter. The drag force is quantified through the equation:

$$\vec{F}_{drag} = \frac{C_d}{8}\pi d_p^2\rho_g|\vec{u}-\vec{v}_i|(\vec{u}-\vec{v}_i)\varepsilon^2 f(\varepsilon)^m \tag{4}$$

m is equal to 1 for laminar interstitial flow. The drag coefficient C_d on a single sphere is given by Schiller and Naumann [5]:

$$C_d = \begin{cases} 24\left(1+0.15\,\mathrm{Re}_p^{0.687}\right)/\mathrm{Re}_p & \mathrm{Re}_p < 1000 \\ 0.44 & \mathrm{Re}_p \geq 1000 \end{cases} \tag{5}$$

A number of empirical relationships of the drag coefficient have been proposed in the litterature. However, there is little information available on the drag of particles in particle clusters. Analytical models are difficult, because the surface of every particle must be taken into account. Most of the data for particle drag have been inferred from sedimentation and uniform fluidization studies. $f(\varepsilon)$ is a porosity function taking into account the presence of other particles on the drag force of an isolated particle as they affect the flow pattern in a uniform suspension. The restriction of the flow spaces between the particles in denser zones results in steeper velocity gradients of the gas phase, thus greater shearing stresses and an increase in resistance of the gas flow. This influence has often been taken into account in numerical studies of gas-particle flows by using the experimental results on sedimentation and fluidization of Richardson and Zaki [6]:

$$f(\varepsilon) = \varepsilon^{-n} \tag{6}$$

with

$$n = \frac{\log\left(\dfrac{\mathrm{Re}_{mf}}{\mathrm{Re}_t}\right)}{\log \varepsilon_{mf}} \tag{7}$$

The collision model proposed by Walton [7] is used to compute the dynamics of instantaneous inelastic non-frontal collisions with friction based on three constant coefficients. The first coefficient e characterizes the incomplete restitution of the normal component of the relative velocity at the point of contact. The second μ arises in collisions involving sliding and has been assumed to be resisted by Coulomb friction. The third β arises in collisions that return a fraction of the energy stored in the elastic deformation of both surfaces to the component of the contact velocity tangent to the spheres. We consider two particles of diameter d_1 and d_2 and with masses m_1 and m_2. The positions of the sphere centers are described by the vectors $\vec{r}_1$ and $\vec{r}_2$. The unit normal $\vec{n}$ at the contact point is defined by:

$$\vec{n} = \frac{\vec{r}_1 - \vec{r}_2}{\left|\vec{r}_1 - \vec{r}_2\right|} \tag{8}$$

The relative velocity $\vec{v}_c$ between the two particles at the contact point is given by :

$$\vec{v}_c = \vec{v}_1 - \vec{v}_2 - \left(\frac{d_1}{2}\vec{\omega}_1 + \frac{d_2}{2}\vec{\omega}_2\right) \times \vec{n} \tag{9}$$

where $\vec{v}_i$ and $\vec{\omega}_i$ are respectively the translation and angular velocities before impact. The impact angle γ is defined as the angle between the normal $\vec{n}$ and the relative velocity $\vec{v}_c$ such that $\gamma \in \left[\frac{\pi}{2}, \pi\right]$. We consider the conservation of kinetic momentum of translation during the collision where $\vec{v}_i^{'}$ represent the velocities after collision :

$$\Delta\vec{P} = m_1\left(\vec{v}_1^{'} - \vec{v}_1\right) = -m_2\left(\vec{v}_2^{'} - \vec{v}_2\right) \tag{10}$$

The normal component of $\Delta\vec{P}$ does not affect the angular velocities. However, the tangential component $\Delta\vec{P}^{(t)}$ provokes a variation of the rotational momentum. represents the We can calculate the velocities after impact if we know the variation of momentum $\Delta\vec{P}$:

$$\vec{v}_1^{'} = \vec{v}_1 + \frac{\Delta\vec{P}}{m_1} \tag{11}$$

$$\vec{v}_2^{'} = \vec{v}_2 - \frac{\Delta\vec{P}}{m_2} \tag{12}$$

$$\vec{\omega}_1^{'} = \vec{\omega}_1 - \frac{d_1}{2I_1}\vec{n} \times \Delta\vec{P} \tag{13}$$

$$\vec{\omega}_2^{'} = \vec{\omega}_2 - \frac{d_2}{2I_2}\vec{n} \times \Delta\vec{P} \tag{14}$$

The Coulomb friction law neglects the fact that an object can pivot on another object. Instead of developping a complex model it is common to introduce a tangential restitution coefficient β. Foerster *et al.* [8] showed that the variation of momentum $\Delta\vec{P}$ during impact could be written :

$$\Delta\vec{P} = -m_{12}(1+e)\vec{v}_c^{(n)} - \frac{2}{7}m_{12}(1+\beta)\vec{v}_c^{(t)} \tag{15}$$

For great values of the impact angle $\gamma \geq \gamma_0$ thus a sliding contact, the tangential restitution coefficient for glass spheres was found $\beta_0 \in [0.35, 0.50]$. For small impact angles $\gamma \leq \gamma_0$, we define $\beta_1 = -1 - (7/2)\mu(1+e)\cot\gamma$, such that the interaction between the particles during impact can be described by the Coulomb friction coefficient and the inelastic restitution coefficient. Foerster *et al.* [8] showed experimentally that the model captures the behaviour of the impact between glass spheres over a wide range of incident angles. The collision parameters used in the present study is taken from these experimental data.

Solution technique

Equations (1) and (2) are solved by a finite volume method. The well known SIMPLE scheme is used as iterative solution procedure. A staggered grid is used with velocity components stored at the control volume surfaces and the scalar variables in the center. The integration of the conservation equations is performed using the power law scheme in space and an implicit scheme in time. A semi-implicit intergration method is used to solve the equation of particle motion (3). In the model two time scales are distinguished which means that two different time steps are used. A *fluid force time step* Δt is used to resolve the gas phase equations, and within this fluid time step several *particle time steps* Δt_p for the hard-sphere particle simulations. The fluid force time step Δt is chosen to be smaller than the particle relaxation time τ_{ig} at maximum packing concentration. In order to save CPU time several *particle control volumes* (PCV) within the *fluid control volume* is used. The fluid control volume is taken large enough to have a representative elementary volume, but little enough to have small changes in flow properties. The surface of the PCVs is chosen to order the particle surface. A minimum particle time step is defined such that any particle having the actual maximum gas velocity only can pass 20 % of the minimum length of the PCV. This calculated timestep is used if it is less than the maximum particle time step Δt_p defined by user.

The gas motion is calculated using the equation (1) and (2) at the time step $t+\Delta t$ with the drag force being estimated at the time step t. Then the particle positions are calculated for the next *particle time step* $t+\Delta t_p$ using equation (3) and then a check for overlapping between particles entirely within the PCVs is performed and then between particles in two adjacent PCVs. Once an overlapping between two particles has been detected the particles are placed in their previous positions. Then the collision dynamics is calculated inducing a change of the translation and rotation velocities and the position of the two particles. The particle's corresponding gas velocity (at time step $t+\Delta t$) and porosity (at time step t) is calculated by linear interpolation within the fluid control volume. After finding the new velocities and positions of all particles at the time step $t+\Delta t$, the void fraction is estimated and the drag forces on every particle summarized within each fluid control volume. Then we continue to compute the gas motion at the time step $t+2\Delta t$.

Objective of this study

Previously, we have studied the influences of the porosity function (taking into account the clustering effect of particles on the isolated particle drag force) on the gas-particle flow behaviour [9] and the influences of interparticle forces of cohesive particles in a dense fluidized bed [10]. In this study we study the influences of the presence of fines on the fluidization of large particles originally in the state of particulate fluidization. The solids mixing rate of large particles increases dramatically within the bed when adding fines (figure 2). This is due to both (a) a decrease in the interstitiel volume thus an increase in gas velocity and (b) an increase of the momentum of large particles during multiple collisions with the fines. We have carried out a systematic study by varying the diameter of the fines and their quantity in order to show this phenomenum.

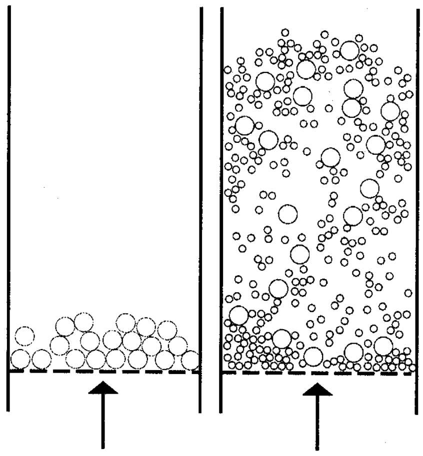

Figure 2. *Fluidization of (a) large particles and (b) large particles with fines.*

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