INFLUENCE OF INTERPARTICLE COHESIVE FORCE ON FLUIDIZED BED BEHAVIOUR BY DEM SIMULATION

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ABSTRACT

A 2D discrete element method simulation of a fluidized bed using 19,200 mono-sized spherical particles is performed. The particles are 500-micron in diameter with density of 1000 kg/m^3. The effects of imposed interparticle cohesive force on minimum fluidization velocity, minimum bubbling velocity and bed expansion are investigated. Minimum fluidization velocity is found to be independent of interparticle force provided the initial packing conditions are held constant. Minimum bubbling velocity is found to increase with increasing interparticle cohesive force. The velocity range in which the bed shows non-bubbling behaviour is significantly affected by interparticle force. The range of bed expansion is found to increase with increasing interparticle cohesive force but the rate of bed expansion with air velocity is found to be independent of interparticle force.

NOMENCLATURE

d_p	Particle diameter in micron
D_b	Diameter of the fluidized bed in m
F	Interparticle force in N
g	Acceleration due to gravity in m/s^2
K	Force Ratio dimensionless
U	Superficial fluidization velocity in m/s
U_{mb}	Minimum bubbling velocity in m/s
U_{mf}	Minimum fluidization velocity in m/s
U_t	Single particle terminal velocity in m/s
U'_t	Intercept of the ln ε vs ln(U) plot at ε = 1
ε	Bed voidage
ρ_f	Fluid density in kg/m^3
ρ_p	Particle density in kg/m^3

INTRODUCTION

In the recent years, the simulation technique based on discrete element method (DEM) has become very popular for simulation of gas-particle systems. In DEM simulation, the particles are traced individually by solving Newton's equations of motion, while the fluid phase is treated as a continuum.

There are two approaches for simulating particle-particle collisions in DEM simulation: soft sphere approach e.g. by Tsuji Kawaguchi and Tanaka (1993) and hard sphere approach e.g. by Hoomans et.al (1996). In the soft sphere model it is possible to estimate the interaction forces using multiple particle contacts that are of prime importance in modelling quasi-stationary systems. The hard sphere approach is quasi instantaneous and the particle interactions are based on binary collisions. According to Mikami et al. (1998), the hard sphere model is not suitable for dense beds, especially when cohesive particles are simulated.

Gera & Tsuji (1998) suggested that DEM simulation is a more appropriate choice than a two fluid model simulation in the modelling of fluidized beds. Based on the DEM simulation developed by Tsuji, Kawaguchi & Tanaka (1993) and Mikami, Kamiya and Horio (1998), Rhodes et.al. (2001) studied the influence of interparticle force on the fluidization characteristics of a bubbling bed. Rhodes et.al. (2001) expressed the interparticle force in terms of a dimensionless parameter, K, which is defined as the ratio of interparticle force, F, to the buoyant weight of the single particle.

$$K = 6 * F / (\pi * d_p^3 * g(\rho_p - \rho_f)) \qquad (1)$$

By varying the magnitude of the input parameter, K, Rhodes et.al. (2001) studied the behaviour of the bed. They also tried to find the boundary between Geldart's group A and B powders. However, Rhodes et.al. (2001) analysis was based on the relative values of the minimum fluidization velocity, U_{mf} and the minimum bubbling velocity, U_{mb} at various magnitude of interparticle force factor, K. Xu et. al. (2002) used Combined Continuum and Discrete Model to study fluidization of Group A powders and revealed significant differences in the force structure within fixed, expanded and fluidized bed. In the present study we investigate the influence of the magnitude of interparticle force on fluidization behaviour. The effects of interparticle force on U_{mf}, U_{mb}, bed expansion and bed pressure drop hysteresis are studied. The results are compared with experimental results.

Table 1: Bed geometry and bed particle detail

Bed Geometry	
Bed width	80 mm
Bed height	60mm
Number of gas nozzles	72
Bed particles	
Number of particles	19200
Particle diameter	500 μm
Particle density	1000 kg/m^3

STRATEGY AND CONDITIONS FOR SIMULATION

All the simulations are performed in a two-dimensional rectangular bed. Table 1 gives the details of the bed geometry and the bed particles used for the simulations.

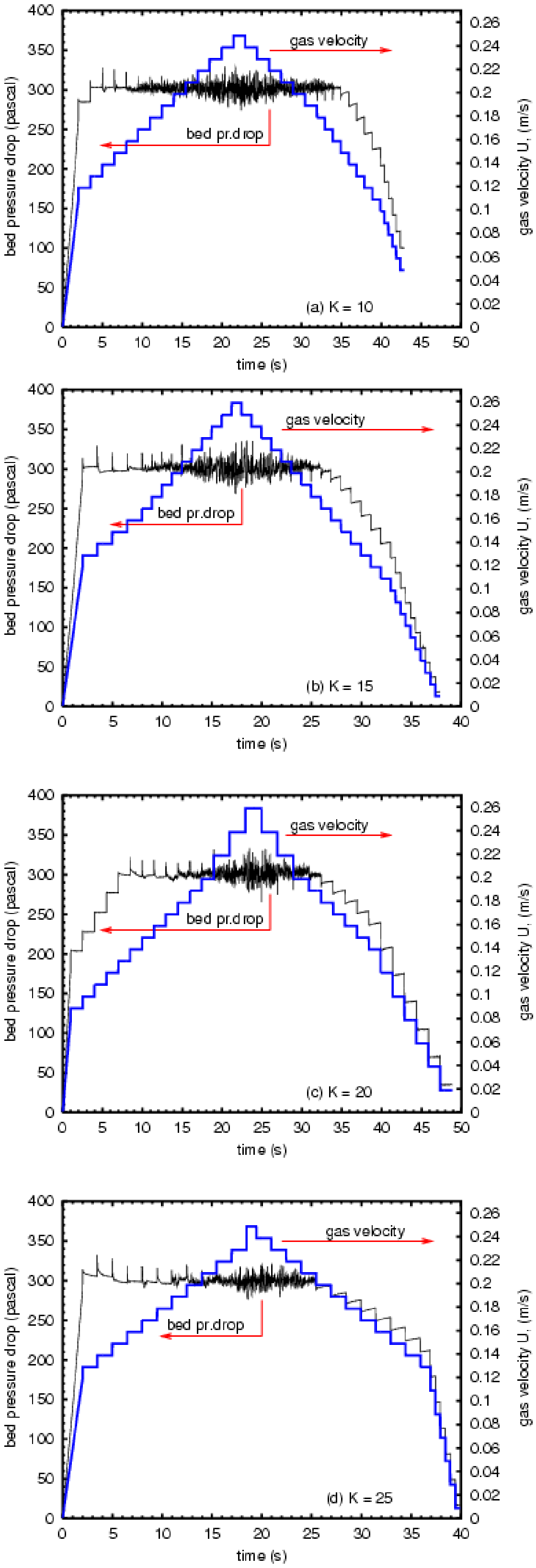

Figure 1: - Typical plots of gas velocity and bed pressure drop variation with time

To study the bed behaviour, the strategy adopted by Rhodes et.al. (2001) is applied here, wherein in the first stage the gas velocity is linearly increased to near but below the estimated minimum fluidization velocity. In the second stage, the gas velocity is increased step by step with a small increment in each step. After each increment the velocity is kept at that value for a small duration. The gas velocity is increased until the bubbling is observed in the bed. The bed is kept in the bubbling condition for some time and then the velocity is decreased to zero in step-by-step manner. Fig. 1 shows a typical velocity variation scheme with time. At each value of the gas velocity, average bed voidage and bed pressure drop are calculated.

RESULTS AND DISCUSSION

Fig. 1 shows the variation of instantaneous bed pressure drop with time and velocity. The output frequency of the pressure drop value is 100. Rhodes et.al. (2001) has identified three types of flow behaviour in a bed.

In type I behaviour bed pressure drop increases approximately linearly with the bed gas velocity and no fluctuation in the pressure drop is observed. Type I behaviour corresponds to fixed bed behaviour. In type II behaviour, each time the gas velocity is increased, the bed pressure drop increases instantly, as in type I , but then decays rapidly to a certain value corresponding approximately to the bed buoyant weight per unit area. The snapshots of the bed exhibiting type II behaviour do not show any bubbles in the bed. Therefore type II behaviour corresponds to non-bubbling fluidized bed. In type III behaviour, the bed pressure drop fluctuates continuously with increase in amplitude as the gas velocity is increased. Study of the corresponding snapshots suggests that these pressure fluctuations are associated with passage of bubbles. Type III behaviour therefore corresponds to a bubbling fluidized bed. The velocity at
the boundary of type I and type II behaviour is the minimum fluidization velocity of the bed. Fig. 1 shows the variation of instantaneous bed pressure drop with time and velocity for various values of interparticle force factor K.

In the increasing velocity range, as shown in Fig. 1, the type II flow behaviour starts at the same bed gas velocity for all values of K. Since type II flow behaviour starts at the minimum fluidization velocity, this indicates that the minimum fluidization velocity is insensitive to the magnitude of interparticle force. For different values of factor, K, the boundary between type II and type III behaviour occurs at a different gas velocity. Increasing the magnitude of factor, K, leads to increase in the gas velocity at which type III behaviour starts and the bed behaves as type II for a longer velocity range. This means, in the presence of interparticle force, the start of bubbling in the bed is shifted to a higher gas velocity. It was also observed that non-bubbling fluidization is possible even when the there is no interparticle force; however the range of gas velocities over which it exists is very small.

Agbim, Nienow and Rowe (1970) found that the presence of interparticle force suppresses bubbling in gas-fluidized bed. Rosenweig (1971) also observed the non-bubbling region in a magnetic fluidized bed and called this non-bubbling region as magnetic stabilized bed. Results of DEM simulation indicate the existence of non-bubbling region that increases with increase in interparticle force. Fig.1 explicitly shows that in the increasing velocity range, the start of bubbling in the bed shifts to a higher gas velocity, in the presence of interparticle force.

Fig. 1 shows that when the velocity of the gas is decreased in the bubbling bed, the behaviour of the bed changes from type III to type I. The bed does not show type II behaviour in the decreasing velocity range. In the decreasing velocity range there is a sharp boundary between the fixed bed and bubbling bed irrespective of the magnitude of the interparticle force. The existence of the sharp boundary between the fixed bed and the bubbling bed suggests that it is more appropriate to determine the minimum bubbling velocity by gradually decreasing gas velocity.

Fig. 2 shows the snapshots of the bed for the simulation with K = 25. This figure shows the three types of bed behaviour just discussed. Fig. 2(a) shows the type I behaviour when fluid velocity is below the minimum fluidization velocity. Fig. 2(b) is the snapshot of non-bubbling, type II behaviour. Readjustment of particles position gives rise to expansion. Expansion in the bed can be clearly noticed from Figs. 2(a) and 2(b). So type II behaviour is non-bubbling fluidized bed that shows expansion with increase in fluid velocity. The snapshot in Fig. 2(c) shows the type III behaviour of bed with bubbling. Fig. 2(d) shows the bed when the fluid velocity in a bubbling bed is gradually reduced to zero.

Fig. 3 shows the bed pressure drop and superficial gas velocity plot for the various values of the interparticle force factor K. Here, the pressure drop value is the time-averaged value of the bed pressure drop for the corresponding gas velocity. Fig. 3 shows that as the value of the interparticle force factor, K is increased, the separation between increasing and decreasing velocity curves increases. The two curves start to separate from each other below a certain values of the gas velocity. In Fig. 3, the point where the increasing and decreasing gas velocity curves separate corresponds to the minimum velocity in Fig. 1 where type III bubbling behaviour of the bed is observed for decreasing gas velocity. The gas velocity at this point is defined as the minimum bubbling velocity U_{mb}. U_{mb} defined on the basis of decreasing velocity curve can be marked clearly on the bed pressure drop-time plot and bed pressure drop-gas velocity plot. The minimum fluidization velocity, U_{mf} marked on Fig. 3 is based on the graphical method suggested by Richardson (1971). From Fig. 3 it is clear that U_{mf} remains constant for all values of the interparticle force factor K, whereas U_{mb} increases with K. The insensitivity of U_{mf} with increasing interparticle force was also observed experimentally by Lucas et al. (1983) and Saxena and Wu (1999).

As shown in Fig. 3, the difference between U_{mb} and U_{mf} increases with increase in the value of K. Table 2 shows the values of the minimum fluidization velocity and minimum bubbling velocity for various values of K obtained from Fig 1 and Fig 3. As shown in Table 2, the values of the minimum fluidization velocity, $U_{mf,}$ obtained from Fig 1 and Fig 3 are in close agreement. The values of the minimum bubbling velocity, U_{mb} , obtained from Fig 1 and Fig 3 match each other within 7 percent. Figs. 1 and 3 together describe the complete behaviour of the fluidized bed.

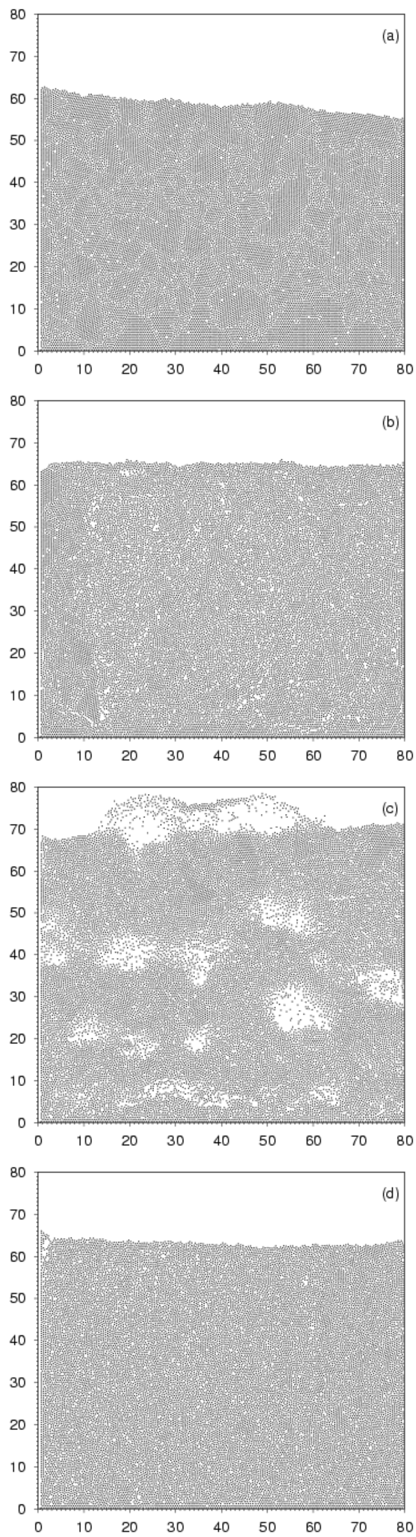

Figure: - 2 Snap shots of the bed showing different type of bed behaviour in the presence of interparticle force. Here K =25. Gas velocity: (a) 0.0 m/s, (b) 0.188m/s, (c) 0.248 m/s, (d) 0.0 m/s (decreasing velocity range)

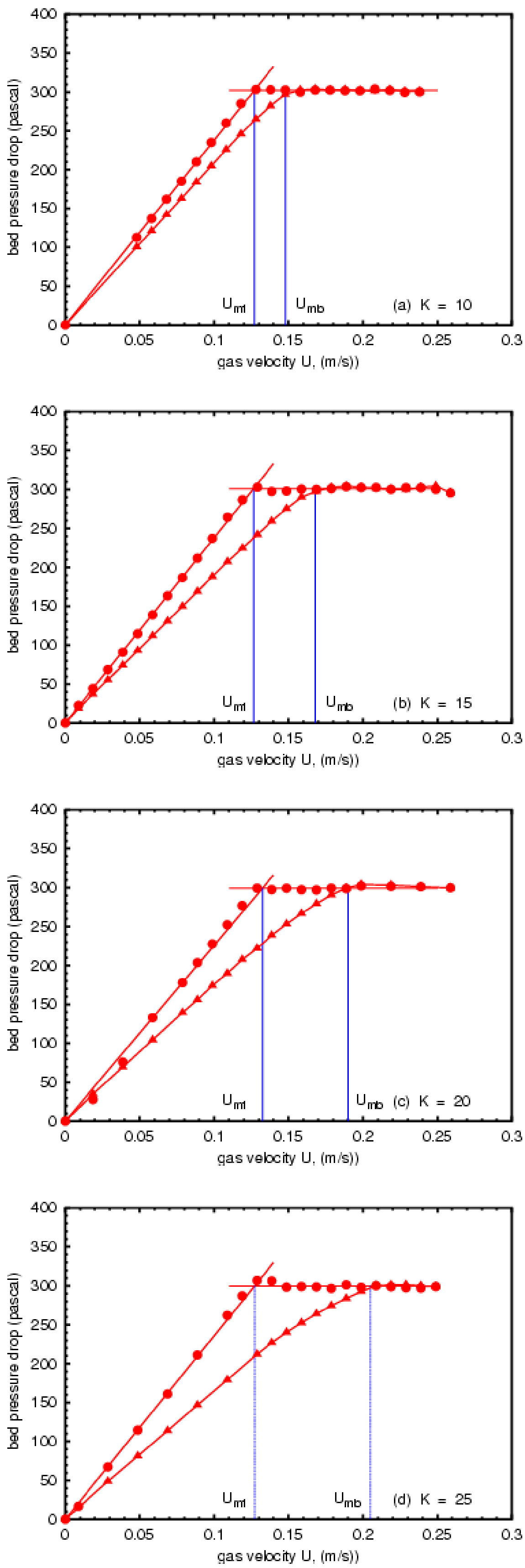

Figure: - 3 Bed behaviour as a function of interparticle force. Bed pressure drop for increasing ● and decreasing ▲ air velocity

Table 2: Comparison of U_{mf} and U_{mb} obtained from bed pressure drop-velocity (Fig. 3) and bed pressure drop-time (Fig. 1) plots

K	U_{mf}		U_{mb}	
	From fig 3	From fig 1	From fig 3	From fig 1
10	0.128	0.129	0.157	0.139
15	0.128	0.129	0.168	0.159
20	0.128	0.139	0.19	0.179
25	0.128	0.129	0.205	0.199
30	0.128	0.129	0.210	0.199

One of the distinct characteristics of type II non-bubbling behaviour is expansion of the bed, which is clearly shown in Fig. 2(b). Bed expansion in the non-bubbling regime of a fluidized bed is given by the Richardson-Zaki relationship.

$$U/U_t = \varepsilon^n \qquad (2)$$

where U is the velocity of the fluid, ε is the bed voidage and U_t is the single particle terminal velocity which is expected to be equal to the intercept of the ln(ε) vs ln (U) plot at ε = 1.

However, Richardson (1971) and Geldart (1986) have used equation (2) with a slight modification.

$$U/U_t^{'} = \varepsilon^n \qquad (3)$$

where U'_t is the intercept of the ln(ε) vs ln (U) plot at ε = 1 and is given by

$$\log(U_t^{'}) = \log(U_t) - d/D_b \qquad (4)$$

Equation (3) is plotted in Fig. 4 for different values of the interparticle force. Fig. 4 is applicable for the increasing velocity range in which the bed shows type II flow behaviour. Within the range of K for which bed behaviour is investigated, the value of n falls in the range of 3.25 to 3.5 and the value of U_t in the range of 1.9 to 2.37. For the bed particles used in the simulation the calculated value of U_t is 1.38. Happel (1958) and Adler (1962) have suggested that equation (3) gives higher values of U as it underestimates the mutual influence of particles. The calculated value of n based on particle terminal Reynold number is 2.98. The value of n obtained from Fig.4 is in close agreement to this. The slight variation in the values of U'_t and n from Fig. 4 may be due to the errors in the employed numerical scheme. Also a true 2-dimensional bed, in which the width of the bed is equal to the particle diameter, may not follow the above equations exactly. However the values of n and U_t appear to be independent of the magnitude of interparticle force. Fig. 4 indicates that for a given particle-fluid system the bed expansion behaviour does not depend on the interparticle force. However increase in the interparticle force increases gas velocity range in which bed expansion takes place

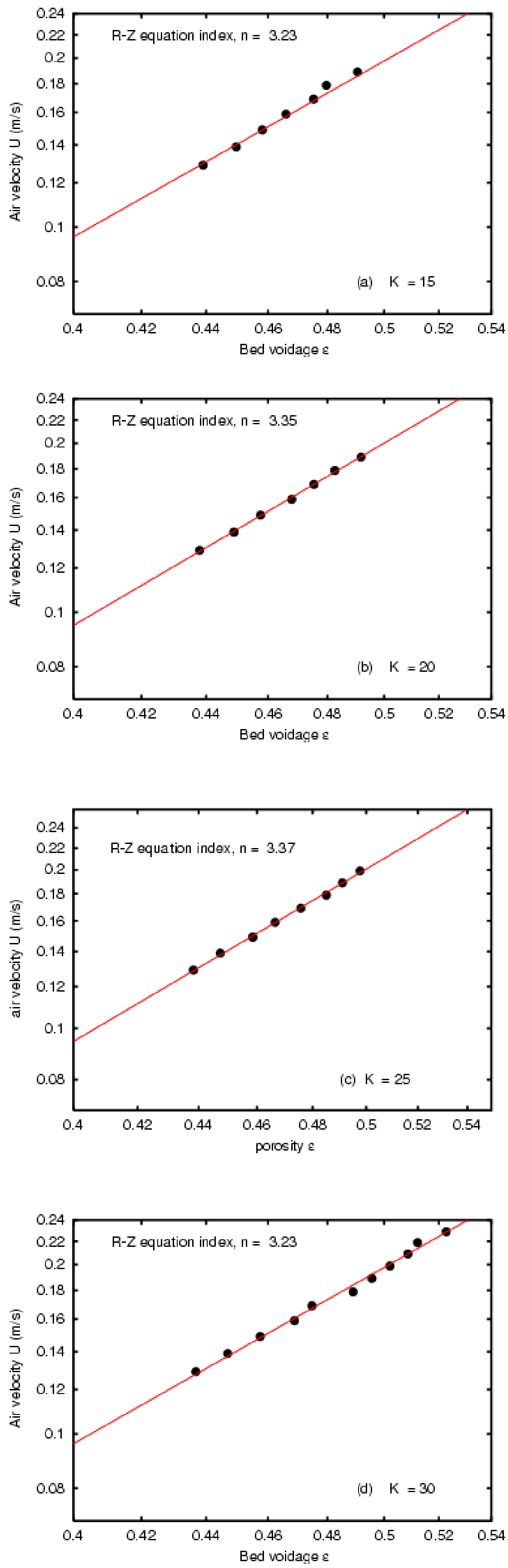

Figure 4: LOG-LOG plot of air velocity with respect to bed voidage at various values of K.

Rietema (1973) demonstrated that interparticle forces gave sufficient mechanical stable structure to a gas fluidized bed and this resulted into expansion of the bed when the velocity of the fluid was increased. The bed expansion behaviour as shown in Fig. 4 is very similar to the expansion behaviour observed experimentally in a magnetic fluidized bed by Pandit, Wang and Rhodes (2003).

CONCLUSIONS

1. DEM simulation of a 2-dimensional rectangular fluidized bed was carried out to investigate the influence of interparticle cohesive force on fluidization behaviour of the particles.
2. Depending on the magnitude of fluidization velocity, the bed shows three distinct types of behaviour; fixed bed, non-bubbling expanding bed and bubbling bed.
3. The increasing velocity range in which the bed exhibits fixed bed behaviour is insensitive to the interparticle force but that for non-bubbling expanding behaviour increases with increase in interparticle force.
4. The minimum fluidization velocity of a bed for a given fluid-particle system measured by increasing gas velocity is independent of the externally imposed interparticle force provided the initial voidage of the packed bed is constant. However the minimum bubbling velocity for a given fluid-particle system increases with the increasing interparticle force.
5. The expansion in the non-bubbling fluidized bed is described by the Richardson-Zaki form of equation. For a given particle-fluid system the bed expansion behaviour is insensitive to interparticle force. However the maximum bed expansion obtained before the start of bubbling in the bed, increases with increasing interparticle force.

REFERENCES

TSUJI, Y., KAWAGUCHI, T. and TANAKA, T., (1993). *"Discrete particle simulation of a fluidized bed".* Powder Technology 77, p. 79

HOOMANS, B.P.B., KUIPERS, J.A.M., BRIELS, W.J. AND VAN SWAAIJ, W.P.M., (1996). *" Discrete particle simulation of bubble and slug formation in a two-dimensional gas-fluidized bed: A hard-sphere approach."* Chemical Engineering Science 51, p. 99

D. GERA, M. GAUTAM, Y. TSUJI, T. KAWAGUChi and T. TANAKA (1998) *"Computer simulation of bubbles in large-particle fluidized beds"* Powder Technology 98(1), p38-47

MIKAMI, T., KAMIYA, H. and HORIO, M., (1998). *"Numerical simulation of cohesive powder behaviour in a fluidized bed."* Chemical Engineering Science 53, p. 1927

M. J. RHODES, X. S. WANG, M. NGUYEN, P. STEWART and K. LIFFMAN, (2001) *"Use of discrete element method simulation in studying fluidization characteristics: influence of interparticle force"* Chemical Engineering Science, Volume 56, Issue 8, April 2001, Pages 2859-2866

B.H. XU, Y. C. ZHOU, A.B. YU and P.ZULLI (2003) *"Force structure in gas fluidized bed of fine* *powders"* World Conference on Particle Technology- IV. Sydney Australia (2003)

AGBIM, J.A., NIENOW, A.W., and ROWE, P.N.(1971) *"Interparticle forces that suppress bubbling in gas fluidized bed"* Chemical Engineering Science Vol. 26, p 1293.

ROSENSWEIG, R.E. (1979) "*Fluidization: Hydrodynamic stabilization with a magnetic field*" Science Vol. 204, p 4388

RICHARDSON J.F. (1971) "*Incipient fluidization and particulate system" Fluidization "* by J.F. Davidson & D. Harrison, Chapter 2 p 26

LUCAS, A., CASA, J., and PUIGJANER, L. (1983) *"Fluidized bed stabilization with a magnetic field: Transition conditions and mixed systems"* (p. 129). In D. Kunii, & R. Toei (Eds.), Fluidization. New York: Engineering Foundation.

SAXENA, S.C. & WU, W.Y., (1999). *"Hydrodynamic characteristics of magnetically stabilized fluidized admixture beds of iron and copper particles."* Canadian Journal of Chemical Engineering 77, p. 312

GELDART, D. (1986) *"Single Particles, Fixed and Quiescent Beds"* in Gas Fluidization Technology Edited by Geldart D. Chapter 2 p 26

HAPPEL, J. (1958) *"Viscous flow in multi particle systems: Slow motion of fluids relative to beds of spherical particles*" A.I.Ch.E.J 4, p 197.

ADLER, I.L. & HAPPEL, J. (1962). *"The fluidization of uniform smooth sphere in liquid media"* Chem. Eng. Progr. Symp. Ser. No. 38 vol.58 p 98.

RIETEMA K. (1973*) "The effefct of interparticle forces on the expansion of a homogeneous gas fluidized bed"* Chemical Engineering Science Vol. 28, p 1493.

PANDIT, Jai Kant, WANG, X.S., RHODES, M.J (2003) "*Study of Fluidization Behaviour in Presence of Externally Imposed Interparticle Force*" paper 109 presented at Chemeca 2003, Adelaide, Australia. 28 September- 01 October 2003

APPENDIX (MATHEMATICAL MODELLING)

The mathematical models consist of equation of particle motion and equation of fluid.

PARTICLE MOTION

The particle movement is evaluated by the Newton equation of motion. Equations of translational and rotational particle motion are given by

$$\vec{a}_s = \vec{F}/m + \vec{g} \qquad \text{(A.1)}$$

$$\vec{\alpha} = \vec{T}/I \qquad \text{(A.2)}$$

where $\vec{a}_s$ is linear acceleration of particle, $\vec{F}$ is force acting on particle, m is mass of particle, $\vec{\alpha}$ is angular acceleration of particle , $\vec{T}$ is torque caused by contact forces and I is moment of inertia of particle. The force acting on particles consists of the particle contact force ($\vec{f}_c$) and the force exerted by surrounding fluids ($\vec{f}_d$).

$$\vec{F} = \vec{f}_c + \vec{f}_d \qquad \text{(A.3)}$$

The model estimates the contact forces using the concept of spring, dash-pot and friction slider. The details of particle contact forces are given by Tsuji, Kawaguchi and Tanaka (1993).

FLUID FLOW

The motion of fluid is described by the equation of continuity and the equation of momentum conservation with the local mean variables. The fluid is assumed to be incompressible and inviscid.

Equation of continuity:

$$\frac{\partial \varepsilon}{\partial t} + (\nabla.\varepsilon\vec{v}) = 0 \qquad \text{(A.4)}$$

Equation of momentum conservation:

$$\frac{\partial(\varepsilon\vec{v})}{\partial t} + (\vec{v}.\nabla)\varepsilon\vec{v} = -\frac{\varepsilon\nabla p}{\rho_f} + f_{si} \qquad \text{(A.5)}$$

where $\vec{v}$ is velocity vector of fluid, p is pressure of fluid and f_{si} is the fluid drag force exerted to the particles

$$f_{si} = \frac{\beta}{\rho_f}(\vec{u}_p - \vec{v}) \qquad \text{(A.6)}$$

where $\vec{u}_p$ is the particle velocity vector averaged in a cell. The coefficient β depends on the voidage and is given by

for $\varepsilon \le 0.8$

$$\beta = \frac{\mu(1-\varepsilon)}{d_p^2 \varepsilon}[150(1-\varepsilon) + 1.75\,\mathrm{Re}] \qquad \text{(A.7)}$$

for $\varepsilon > 0.8$

$$\beta = \frac{3}{4} C_D \frac{\mu(1-\varepsilon)}{d_p^2} \varepsilon^{-2.7}\,\mathrm{Re} \qquad \text{(A.8)}$$

where C_D is drag force on each single particle and Re is particle Reynolds number.

The equation of fluid motion was solved simultaneously with equation of particle motion.