Comparison of Representations for Particle - Particle Interactions in a Gas - Solid Fluidised Bed

R. A. Bell[1,2], P. J. Witt[1,2], A. K. Easton[1,2] and M. P. Schwarz[2,3]

1. Swinburne University of Technology, Hawthorn, Victoria
2. CRC - New Technologies for Power Generation From Low Rank Coal, Mulgrave, Victoria
3. C.S.I.R.O. Division of Minerals, Clayton, Victoria

ABSTRACT

Fluidised bed technology is currently being investigated by the power generation industry for use in gasification, combustion and drying of low rank coal. Scale-up of this technology is a problem because the physical behaviour is not fully understood. The computational code CFX4 is being used to understand behaviour in a fluidised bed which ultimately will result in more accurate methods of plant scaling from small scale pilot plant to large scale production plant.

The aim of the current work is to develop a multiple particle size model which will represent multiphase flow in fluidised beds. Two-dimensional transient behaviour of a gas-solid fluidised bed is simulated using an isothermal multiphase Eulerian - Eulerian finite volume model. Each phase is described in terms of continuum equations for the conservation of mass and momentum. An equation representing the interaction between particles of different sizes in a gas - solid fluidised bed was modified and compared with two different equations. Results show the importance of including these interactions in models.

1. NOTATION AND UNITS

Symbol	Term and units
c	Compaction modulus
C_d	Drag coefficient
d_p	Particle diameter, m
e	Coefficient of restitution
g	Acceleration due to gravity
$G(\varepsilon_g)$	Solids elastic modulus, Pa
P	Pressure, Pa
s_i	Source term
t	Time, s
u_g, u_s	Gas and solids phase x-direction velocity, m/s
V_g, V_s	Gas and solids phase y-direction velocity, m/s
v_{s1}, v_{s2}	Solids phase velocity, m/s

Greek letters

Symbol	Term and units
α	Arbitrary function
β_{ij}	Interaction coefficient, kg/(m^{3}s)
ε_g, ε_{s1}, ε_{s2}	Volume fraction of gas phase and solid phases, *s1* and *s2*
ε^*	Compaction gas phase volume fraction
ϕ_{s1}, ϕ_{s2}	Volume fraction at maximum packing of solid phases, *s1* and *s2*
σ_s	Sphericity
μ_g	Gas viscosity, Pa.s
ρ_g, ρ_{s1}, ρ_{s2}	Density of gas phase and solid phases, *s1* and *s2*, kg/m^3

Subscripts

g	Gas
$s1$	Solid 1
$s2$	Solid 2

2. INTRODUCTION

The power generation industry is currently interested in developing new technologies which efficiently use low rank coal. A majority of the technologies being investigated utilise fluidised beds as gasifiers, combustors and driers. Although fluidised bed technology has been in existence for a number of years, the physical behaviour involved is not fully understood. Work is continually being undertaken to understand the characteristic behaviour of fluidised bed systems and possible problems with scale-up. Most experimental work is performed on small scale pilot plants. When scaled up to full size production plant, the behaviour does not necessarily reflect characteristics observed in smaller models. The usual solution to this problem at present is to build plants of differing scales until full scale is achieved but this can be very costly and time consuming.

CFD techniques provide an improved method to better understand the processes involved in a fluidised bed. Once the CFD model is validated against physical modelling data from smaller scale plants, the model can be used to predict the behaviour of medium scale production plants, reducing the number of pilot plants required.

Previous CFD fluidised bed models are limited to one particle size and density only, however an industrial fluidised bed can contain many different particle sizes with different densities. An important parameter determining the behaviour of the bed is the interaction between particles of different size. It is the aim of this work to develop a model which considers more than one particle size or density to extend the range of industrial fluidised beds which can be modelled.

3. THEORETICAL MODEL

A two dimensional transient model of a gas-solid fluidised bed is simulated using an isothermal multiphase Eulerian - Eulerian finite volume model. There are three phases in the model, one gas and two solid. Each are described in terms of continuum equations for the conservation of mass and momentum.

The continuity and momentum equations for two dimensional flow as given by Syamlal (1985) are

$$\frac{\partial(\varepsilon_i \rho_i)}{\partial t} + \nabla.(\varepsilon_i \rho_i \mathbf{u}_i) = 0 \tag{1}$$

$$\frac{\partial(\varepsilon_i \rho_i \mathbf{u}_i)}{\partial t} + \nabla.(\varepsilon_i \rho_i \mathbf{u}_i \mathbf{u}_i) = -\varepsilon_i \nabla P + \beta_{ij}(\mathbf{u}_j - \mathbf{u}_i) + \varepsilon_i \rho_i \mathbf{g} + \mathbf{s}_i \tag{2}$$

where $i = g$, $s1$ and $s2$
$j = g$, $s1$ and $s2$ $(j \neq i)$

and ε_i is the phase volume fraction, ρ_i is the phase density, t is time, $\mathbf{u}_i$ is the phase velocity vector, P is pressure, $\mathbf{g}$ is the acceleration due to gravity, β_{ij} is the interaction coefficient and $\mathbf{s}_i$ is the source term.

Table 1 contains some of the necessary constitutive equations required to solve the continuum equations, namely the particle-particle interaction coefficient and the gas-particle interaction coefficient.

3.1 Particle - Particle Interaction

The particle - particle interaction coefficient, β_{ij}, is used in models containing particles of more than one size and density. The coefficient accounts for collisions and contact between particles of different size by transferring momentum between phases.

Preliminary investigation into limited published work shows there is no superior relationship for the particle-particle interaction in a fluidised bed. An early version of an equation for particle- particle interaction applied to the dilute phase only (Arastoopour *et al*, 1982).

Equation (3), originated from a more recent equation (Gidaspow *et al* 1990) for particle - particle interactions, β_{ij} in a dense bed where α is an arbitrary function and e is the restitution coefficient.

Gidaspow *et al* (1986) gave a relationship for the particle - particle interaction in a dense bed, Equation (4), which originated from a thesis (Syamlal, 1985). Another equation by O'Brien and Syamlal (1990) was found to be very similar to Gidaspow *et al* (1986). During investigation of these relationships, the equations were found to be unsuitable. The term found in the denominator of Equation (4),

Table 1: Constitutive Relations

Particle - particle interaction

$$\beta_{ij,i,j\neq g} = \frac{3}{2}\alpha(1+e)\frac{\rho_i\rho_j\varepsilon_i\varepsilon_j\left(d_i+d_j\right)^2}{\rho_i d_i^{\,3}+\rho_j d_j^{\,3}}\left|v_i-v_j\right| \tag{3}$$

$$\beta_{ij,i,j\neq g} = \frac{1}{2}\alpha(1+e)\frac{\rho_i\rho_j\varepsilon_i\varepsilon_j\left(d_i+d_j\right)^2\left[1+3\left(\frac{\varepsilon_{kl}}{\varepsilon_k+\varepsilon_l}\right)^{\frac{1}{3}}\right]}{\left(\rho_i d_i^{\,3}+\rho_j d_j^{\,3}\right)\left[\left(\frac{\varepsilon_{kl}}{\varepsilon_k+\varepsilon_l}\right)^{\frac{1}{3}}-1\right]}\left|v_i-v_j\right| \tag{4}$$

$$\beta_{ij,i,j\neq g} = \frac{2\alpha(1+e)\varepsilon_i\rho_i\varepsilon_j\rho_j\left(d_i+d_j\right)^2\left[1+\frac{3}{4}\left(\frac{\varepsilon_{ij}}{\varepsilon_i+\varepsilon_j}\right)^{\frac{1}{3}}\right]}{\left(d_i^{\,3}\rho_i+d_j^{\,3}\rho_j\right)\left(\frac{\varepsilon_{ij}}{\varepsilon_i+\varepsilon_j}\right)^{\frac{1}{3}}}\left|v_i-v_j\right| \tag{5}$$

where $\varepsilon_{ij} = \left[\left(\phi_i-\phi_j\right)+(1-a)\left(1-\phi_i\right)\phi_j\right]\left[\phi_i+\left(1-\phi_i\right)\phi_j\right]\frac{\overline{X}_i}{\phi_i}+\phi_j$ for $\overline{X}_i \le \frac{\phi_i}{\phi_i+\left(1-\phi_i\right)\phi_j}$ (6)

$\varepsilon_{ij} = (1-a)\left[\phi_i+\left(1-\phi_i\right)\phi_j\right]\overline{X}_i+\phi_i$ for $\overline{X}_i \ge \frac{\left(1-\phi_i\right)\phi_j}{\phi_i+\left(1-\phi_i\right)\phi_j}$ (7)

and $a = \sqrt{\frac{d_j}{d_i}}$ $\quad d_i \le d_j$

Gas - particle interaction

$$\beta_{gj,j\neq g} = \begin{cases} \left(150\frac{\varepsilon_j^{\,2}\mu_g}{\varepsilon_g\left(d_p\sigma_s\right)_j^{\,2}}\right)\left(\frac{1-\varepsilon_g}{\varepsilon_j}\right)+1.75\frac{\rho_g\left|V_g-V_j\right|\varepsilon_j}{\left(d_p\sigma_s\right)_j} & \varepsilon_g \le 0.8 \\ \frac{3}{4}C_d\frac{\varepsilon_g\left|V_g-V_j\right|\rho_g\varepsilon_j}{\left(d_p\sigma_s\right)_j}\varepsilon_g^{-2.7} & \varepsilon_g \le 0.8 \end{cases} \tag{8}$$

where $\varepsilon_g + \varepsilon_{s1} + \varepsilon_{s2} = 1$

$$\left(\frac{\varepsilon_{kl}}{\varepsilon_k + \varepsilon_l}\right)^{\frac{1}{3}} - 1$$

will always be negative, making β_{ij} negative. This results in large instabilities in the CFD model and incorrect results.

The authors followed though the derivation of Equation (4) by Syamlal (1985) and modified it to give a new relationship for particle - particle interactions, Equation (5). ε_{ij} is the maximum solids volume fraction of a random close packed structure (Fedors and Landel, 1979) shown as Equations (6) and (7). ϕ_i and ϕ_j are the solids volume fractions at maximum packing.

This paper compares the results of numerical experiments based on Equation (3), Equation (5) and a case where there are no particle - particle interactions, $\beta_{s1,s2} = 0$.

3.2 Gas - Particle Interaction

Frictional drag occurring between the gas and mono - sized fixed density particles is represented by the gas - particle interaction coefficient, β_{gj}. In the current work, the gas - particle interaction is given by Equation (8). For each of the solid phases, there is a β_{gj} to account for gas - solid interaction forces. Details of the drag coefficient, C_d are given by Bouillard *et al* (1989).

3.3 Solids Stress

The solids stress term is added to each solid phase momentum equation to account for forces arising from the packing of particles.

The normal component of the solids Coulombic stress is calculated from Equation (9) using the solids elastic modulus, $G(\varepsilon_g)$ (Bouillard *et al*, 1989) from Equation (10).

$$s_i = G(\varepsilon_g)\nabla\varepsilon_g \qquad (9)$$

where

$$G(\varepsilon_g) = exp\left[-c(\varepsilon_g - \varepsilon^*)\right] \qquad (10)$$

c is the compaction modulus and ε^* is the compaction gas phase volume fraction.

These equations are not strictly correct for use with multiple particle sizes. The packing of particles will depend on the size and volume fraction of each solid phase. Therefore, the solids stress equation should be altered to reflect this behaviour. However, as the solid stress term is only important as the solids volume fraction approaches the packing fraction which is above the minimum fluidisation volume fraction, the current approach is considered adequate.

4. EXAMPLE DETAILS

The current example is based on experimental work reported by Gidaspow *et al* (1986) which simulates mixing of two different sized particles in a fluidised bed containing a central jet. The bed diameter is 0.04 m and the jet width is 0.0127 m. Only half the bed is modelled using symmetry to reduce computational time. There are 31 cells in the x-direction each with a width of 6.35×10^{-3} m and 67 in the y-direction with a height of 1.08×10^{-2} m. The time step used is 5×10^{-4} s. The air jet velocity is set at 5 m/s and air flow through the distributor is 0.506 m/s.

Some additional assumptions have been made. The air is assumed to have a density of 1.2 kg/m^3; to be inviscid; and the minimum fluidisation porosity of the bed is assumed to be 0.42. Pressure at the top of the bed is assumed to be atmospheric at 101.3 kPa. The restitution coefficient of both particle sizes is 0.9 and both the sphericity and α are assumed to be 1.0. The compaction modulus is assumed to be 600 and the compaction gas phase volume fraction is assumed to be 0.376.

Initially, the bed contains two distinct layers of particles. The bottom layer which is 0.146 m deep is Ballotini particles having a diameter of 820 μm and a density of 2940 kg/m^3. The top layer is hollow glass beads with a diameter of 241 μm and a density of 2420 kg/m^3. This layer is assumed to also be 0.146 m deep.

5. RESULTS

All results contained in this paper were obtained by using the computer code CFX4 (CFDS, 1995). The code is run on a SUN SPARC 10 to obtain results for three cases. The computation takes approximately 33 hours to complete 1.0 s of real time. Post processing of the results is performed on a PC using the graphical analysis software TECPLOT.

Three different runs are compared in this paper. In run 1, no particle - particle interactions are included. Run 2 uses Equation (3) for the particle - particle interactions and run 3 uses Equation (5). In all cases, Equation (9) is used for the gas - particle interaction.

Figures 1,2 and 3 show computed results at time t = 0.4 s of runs 1, 2 and 3 respectively. The plots show the particle distributions of the Ballotini particles on the left and the glass beads on the right.

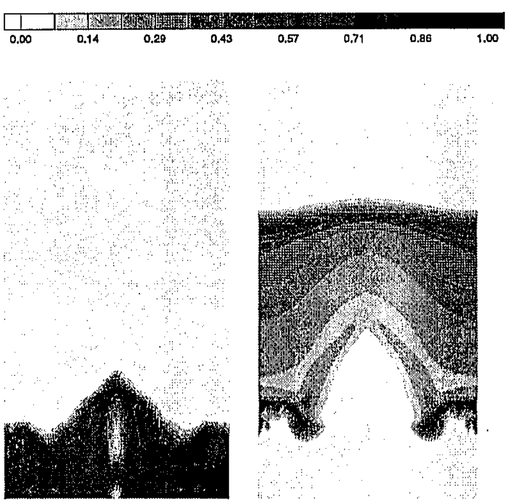

Figure 1: Volume fraction plots showing mixing of the Ballotini particles (left) and hollow glass beads (right) at time t = 0.4 s. No particle - particle interaction included.

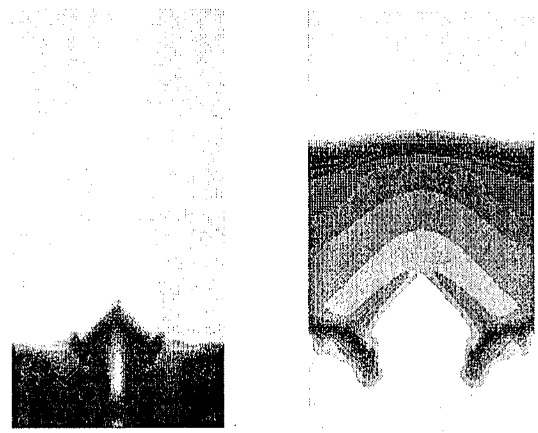

Figure 2: Volume fraction plots showing mixing of the Ballotini particles (left) and hollow glass beads (right) at time t = 0.4 s. Particle - particle interaction added via Equation (3)

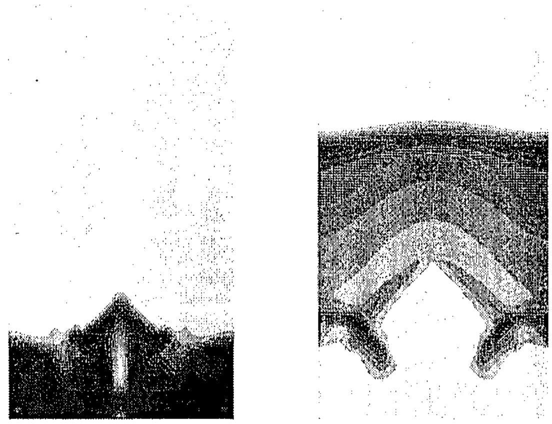

Figure 3: Volume fraction plots showing mixing of the Ballotini particles (left) and hollow glass beads (right) at time t = 0.4 s. Particle - particle interaction added via Equation (5).

Figures 4, 5 and 6 show computed results from the model at time t = 0.8 s of runs 1, 2 and 3 respectively. Once again, the plots show the particle distributions of the Ballotini particles on the left and the glass beads on the right.

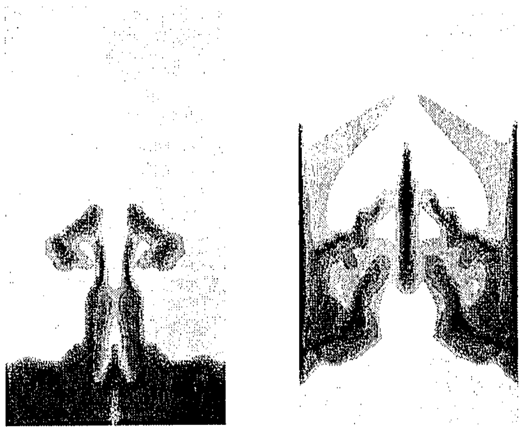

Figure 4: Volume fraction plots showing mixing of the Ballotini particles (left) and hollow glass beads (right) at time 0.8 s. No particle - particle interaction included.

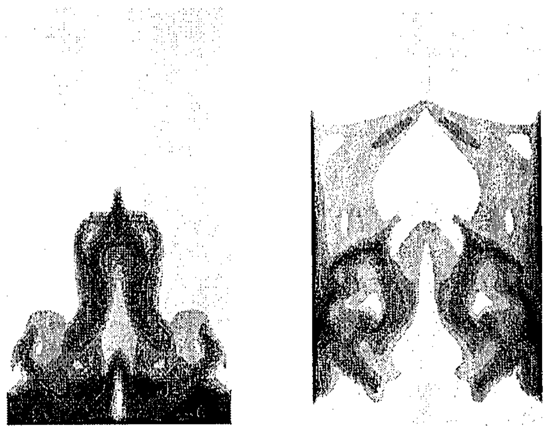

Figure 6: Volume fraction plots showing mixing of the Ballotini particles (left) and hollow glass beads (right) at time t = 0.8 s. Particle - particle interaction added via Equation (5).

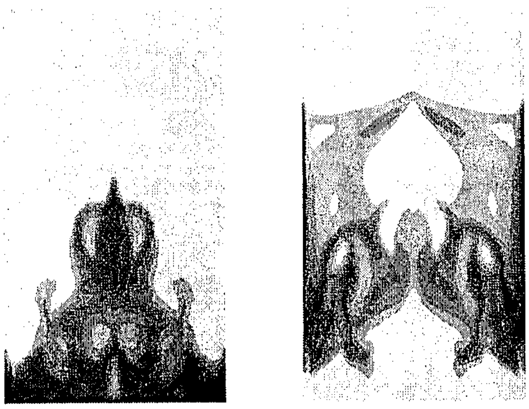

Figure 5: Volume fraction plots showing mixing of the Ballotini particles (left) and hollow glass beads (right) at time t = 0.8 s. Particle - particle interaction added via Equation (3)

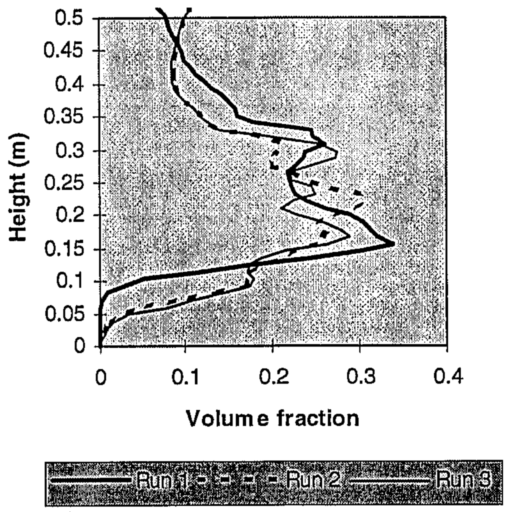

Figure 7: Average volume fraction versus bed height at time t = 0.8 s for glass beads phase.

Figure 7 is a plot of the average volume fraction over a cross-section of the bed versus bed height at time t = 0.8 s for the glass beads phase. It compares the three runs and shows differences in the three relationships for particle - particle interactions used.

Spencer *et al* (1996) gives a comparison of the results of Run 2 with previously obtained results by Gidaspow et al (1986).

6. DISCUSSION

It can be seen that the overall results are very similar. However, there are some significant differences which will become more important as simulation time increases.

The Ballotini phase in Figure 1 at time t = 0.4 s appear quite dense. The rising bubble seen here is not the classic shape expected of a bubble because of the high jet velocity at this point. The glass beads phase has expanded and is beginning to mix. The dense regions towards the bottom will get drawn into the wake of the bubble in the Ballotini phase. Figure 2 shows similar behaviour, however, there appears to be a little more mixing occurring with the glass beads phase being drawn further down into the Ballotini phase. It can be seen from Figure 1 that the Ballotini phase is rising up as a dense region rather than mixing in close to the interface as it does in Figure 2. Figure 3 is almost identical to Figure 2. The similarities in these figures is because of the lack of mixing occurring and the interactions between particles of different size are only occurring at the interface between the Ballotini phase and the glass beads phase. As time increases, more mixing occurs and the particle - particle interactions become more important.

The Ballotini particles at time t = 0.8 s in Figure 4 are still in a dense mass with a small amount being mixed into the glass beads phase. The glass beads phase has a dense region in the centre under the gas bubble and also a dense mass against the walls showing the typical circulation flow of particles down the walls. Figure 5 is quite different from this with the Ballotini phase mixing more readily with the glass beads phase. There is a dense mass of the Ballotini phase rising up in the wake of the bubble in the glass beads phase. This shows one of the basic mechanisms of mixing. Some of the glass beads phase is also being drawn down into the Ballotini phase as the mixing continues. Figure 6 is quite similar to Figure 5 but predicts a little more mixing. The dense regions are not as dense as in the previous figure except for the glass beads phase moving down the walls.

From Figure 7, it can be seen that run 1 with no particle - particle interactions is significantly different from runs 2 and 3. Runs 2 and 3 are very similar except for between bed heights of 0.1 m and 0.32 m. When run 2 predicts a higher volume fraction, run 3 predicts a lower volume fraction and vice versa. This region coincides with a recirculation pattern in the bed. On further investigation, run 3 predicts a larger recirculation region.

It can be seen that the longer the model operates, the more important it is to consider the effect of particle - particle interactions. For an accurate model, these interactions must be included. However, it is still unclear as to which equation should be used to represent the particle - particle interaction. Further comparison of numerical results with experimental results will help to solve this problem.

7. CONCLUSIONS

Transient behaviour of a two-dimensional gas-solid fluidised bed containing two different particle sizes was simulated using an isothermal multiphase Eulerian - Eulerian finite volume model. The model contained three phases where one was gas and two were solid.

An equation for the particle - particle interaction coefficient has been presented and compared with a model containing no particle - particle interactions and a model with a different equation for the coefficient. Results were obtained using the computer code CFX4. At time t = 0.4 s few differences between the models were observed because interactions of different sized particles were only occurring in a small area along the interface between the two phases. At time t = 0.8 s, the interactions were more widespread leading to significant differences in results. Run 1, with no particle - particle interactions showed little mixing whereas Runs 2 and 3, with particle - particle interactions, showed widespread mixing between the two phases and run 3 predicted a larger recirculation region.

Further work is continuing on these relationships to determine an appropriate representation for particle - particle interactions in a gas-solid fluidised bed.

8. ACKNOWLEDGMENTS

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