CFD Modeling of a Binary Liquid-Solid Fluidized Bed

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Abstract: In this study, the multi fluid Eulerian computational fluid dynamics (CFD) model with granular flow extension was used to simulate a binary liquid-solid fluidized bed in the laminar flow, temperature among 20-25°C and below atmospheric pressure. The superficial water velocity was 0.0025 to 0.05 m/s. Governing equations were discreted by using the two-dimension finite volume method. It was concluded that the simulated data were in good agreement with the experimental ones obtained from the literature. In addition, the predicted values of bed voidage, obtained from CFD simulation, have been compared with the predicted value from the property average model and serial model. In addition, the results show that the simulation predicted bed voidage was in good agreement with the experimental data. The CFD simulation results and experimental data demonstrated also that the bed expansion increased by increasing superficial water velocity.

Key words: Binary liquid-solid · Fluidized bed · Overall voidage · CFD

INTRODUCTION

The liquid-solid fluidized beds have been widely used in industry for hydrometallurgical operations, catalytic cracking, ion exchange, adsorption, crystallization, sedimentation, particle classification, etc. In these operations, particle size distribution is encountered in practice as well as bed density distribution. The liquid-solid fluidized beds contain a wide range of particle size and bed density distribution. It is important to be able to predict the bed expansion, particle segregation and intermixing. The particle size and bed density distribution govern the equipment volume, depend on the phase in which the reaction (the mass transfer) takes place. Further, the spatial distribution of solid phase holdup governs the flow pattern of solid and liquid phases. Thus it affects the extent of intermixing and the rates of mass and heat transfer directly.

In this article, the voidage and bed expansion of binary liquid-solid fluidized beds have been simulated by FLUENT®6.3.26 software. The model was defined based on a two-dimensional Eulerian-Eulerian approach. Furthermore, the finite volume method was used to discrete governing equations. Solid and liquid phases were treated as fully interpenetrating continua based on extended granular flow theory. The simulations were carried out in two-dimensional (2D) rectangular Cartesian coordinates, ignoring front and rear wall effects.

MATERIALS AND METHODS

Physical Model: The simulation conditions have been set similar to the experiment circumstances, applied by Asif [1]. Five of Asif experiments were selected. Their conditions are tabulated in Table 1.

The binary mixture of particles, consist of 1396µm polyethylene terephthalate resin (Pet) and 2465µm Glass beads (GB) with the various volume fraction of larger component (X1), were used through the bed. The particles’ sizes and densities are tabulated in Table 2.

Geometry and Mesh: GAMBIT® 2.2.16 was used to produce 2D rectangular geometry with width of 60mm and height of 1000mm. In the all cases, the column to particle diameter ratio was taken greater than 25 in order to eliminate the wall effects. The geometry has been created in GAMBIT® shown in Figure 1 and exported into FLUENT®.
Table 1: Physical properties of particle samples used\(^{1}\)

<table>
<thead>
<tr>
<th>Solid species</th>
<th>Size (µm)</th>
<th>Density (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene Terephthalate resin (Pet)</td>
<td>2790</td>
<td>1396</td>
</tr>
<tr>
<td>Glass</td>
<td>462.5 (average)</td>
<td>2465</td>
</tr>
</tbody>
</table>

Table 2: Pet glass system

<table>
<thead>
<tr>
<th>Weight (g)</th>
<th>Experimental</th>
<th>Glass</th>
<th>Total solid (cm(^3))</th>
<th>(X_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>97</td>
<td>500</td>
<td>272.3</td>
<td>0.255</td>
</tr>
<tr>
<td>4</td>
<td>184</td>
<td>500</td>
<td>334.6</td>
<td>0.394</td>
</tr>
<tr>
<td>5</td>
<td>412</td>
<td>500</td>
<td>498</td>
<td>0.593</td>
</tr>
<tr>
<td>6</td>
<td>825</td>
<td>500</td>
<td>793.8</td>
<td>0.744</td>
</tr>
<tr>
<td>8</td>
<td>690</td>
<td>200</td>
<td>575.4</td>
<td>0.859</td>
</tr>
</tbody>
</table>

Fig. 1: Mesh size 30×5

Fig. 2: Comparison of overall voidage as a function of time for different mesh resolutions. (Exp-3 at \(U_w=0.036\) m/s, \(e_0=0.4082\))

A grid independence was only checked for one of experiments (Exp-3, \(U_w=0.036\) mm/s) with four different mesh sizes (20×350, 24×400, 30×500, 40×660) in the Figure 2. It was observed that the average voidage of the bed varies by 9%; while, the grid size was varied from 3 to 2.5 mm. Further, decrease in particle size from 2.5 to 2 mm resulted into only 6% increase in the average voidage. A very little change (about 1%) in the average voidage of the bed was observed when the grid resolution was increased from 1.5 to 2 mm. Therefore, it was confirmed that, the average voidage of the bed is independent on mesh size. Hence, grid size of 2mm was selected to study more. Other authors, such as Lettieri et al. [2] and Cornelissen et al. [3], have also employed 2 mm grid size in the simulations of solid-liquid fluidized beds.

**CFD Model Formulation:** A two-fluid model was used to model the system. The kinetic theory of granular flow (KTGF) of Gidaspow \(^{4}\) was applied to calculate particulate phase stress. The conservation of mass and momentum provided the governing equations for the interpenetrating liquid and solid phases. The dense solid phase containing in elastic spherical particles has been modeled based on the kinetic theory of granular flow. Details of the physical model and parameters used in simulations are summarized in Tables 3 and 4, respectively.

Two-dimensional CFD simulations were carried out along 60 seconds. Simulation results were then compared with the experimental data. In cases of low velocity fluidization as in the present study, turbulent model wasn’t used to extend previous studies, such as Lettieri et al. [2]. Cornelissen et al. [3], Gidaspow [11] and Mazzei and Lettieri [12]. In this study, no slip wall conditions was applied for the liquid phase and partially slip wall condition was applied for the particle phase, as proposed [13]. Over the top outlet, the pressure was specified as the atmospheric pressure; whereas, over the bottom inlet, a uniform liquid velocity profile is imposed. It should be considered that the present simulation setup corresponds to the experiment of Asif [1]. The governing equations were solved by the commercial FLUENT\(^{®}\) CFD code based on the laminar flow option in double precision mode. The simulations were analyzed by the line rake function in FLUENT\(^{®}\). Since, the upper bed surface is not flat, evenly at higher fluidization velocities; spaced vertical lines were used to estimation average overall bed height to determine the overall bed voidage.

Figures 3(a) and 3(b) show the volume fractions of pet and glass in the reactor by Exp-4 (\(X_1=0.593\)) at superficial water velocity (\(U_w\)) of 0.0178m/s, respectively. Figure 3(c) demonstrates the meshes generation. Figure 3(d) illustrates the distribution of overall voidage in the reactor by Exp-4 at the \(U_w\), equalized to 0.0178m/s.
Table 3: Summary of parameters used in numerical simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor size</td>
<td>0.060m×1m</td>
</tr>
<tr>
<td>Grid number</td>
<td>30∗500 (-)</td>
</tr>
<tr>
<td>Time step</td>
<td>5∗10⁻²s</td>
</tr>
<tr>
<td>Max Iterations</td>
<td>20 (-)</td>
</tr>
<tr>
<td>$\epsilon_{min}$</td>
<td>0.63(-)</td>
</tr>
</tbody>
</table>

Table 4: Model equation in Fluent 6.3.26 CFD code

Continuum equation

\[
\frac{\partial}{\partial t}\left(\rho:\mathbf{u}\right) + \nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u}\right) = -\nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u}\right) + \nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u}\right) + \rho \mathbf{g} - k_d(u_d - u_s)
\]

Momentum equation

\[
\frac{\partial}{\partial t}\left(\rho \mathbf{u}\right) + \nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u}\right) = -\nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u}\right) + \nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u}\right) + \rho \mathbf{g} - k_d(u_d - u_s)
\]

Inter-phase drag coefficient of Syamlal-O'Brien model \[5\]

\[
k_d = \frac{3\epsilon_s\epsilon_l}{4\alpha_d^2} \left(\frac{Re}{D}\right)\left|\frac{u_d - u_s}{u_l}\right|
\]

Where $u_{s,t} = 0.5(A = 0.06Re_x + \sqrt{0.06Re_x^2 + 0.12Re_x(2B - A) + A_x^2})$

where $A = 4.14$ & $B = \frac{0.08\epsilon_l}{\epsilon_l + 0.85}$

Inter-phase drag coefficient of Gidaspow \[6\]

\[
k_d = \begin{cases} \frac{3}{4} \frac{C_D}{d_s} \left(\frac{\rho V_x}{\rho U_x}\right)^2 \frac{|u_d - u_s|}{U_x} & \epsilon_s \leq 0.2 \\ \frac{150 \epsilon_s^2 u_d^2}{\epsilon_l \rho U_x} + 1.75 \frac{\rho V_x}{\rho U_x} \frac{|u_d - u_s|}{U_x} & \epsilon_s > 0.2 \end{cases}
\]

Radial distribution function of Ogawa and Umemura

\[
g_d = \left[1 - \left(\frac{\epsilon_s}{\epsilon_{s,max}}\right)^{\frac{1}{3}}\right]^{-1}
\]

Solid shear viscosity

\[
\mu_s = \mu_{s, col} + \mu_{s, kin} + \mu_{s, fr}
\]

\[
\mu_{s, col} = \frac{4}{3} \rho_s \rho_f \left(\frac{\rho_s}{\rho_f}\right) \frac{\mu_s}{\pi} \left[5, 6\right]
\]

\[
\mu_{s, kin} = \frac{\rho_s \rho_f \left(\frac{\rho_s}{\rho_f}\right) \left(1 + \frac{(1 + e)(3\epsilon_s - 1)\epsilon_s g_o}{\epsilon_s}ight)}{6(3 + e)} \left[6\right]
\]

\[
\mu_{s, fr} = \frac{P_s \sin(\Theta_o)}{2 \sqrt{T^2 D}} \left[8\right]
\]

Diffusion coefficient:

\[
k_{\Theta} = \frac{150 \rho_s d_s^2 \sqrt{\rho_s \pi}}{384(1 + e)\rho_f g_o} \left[1 + \frac{6}{5} \frac{(1 + e)\epsilon_s g_o}{\epsilon_s} g_o \right]^2 + 2 \rho_s \rho_f \frac{\lambda_s}{d_s} \left(1 + e\right) g_o \sqrt{\frac{\rho_s}{\pi}}
\]

Solid bulk viscosity:

\[
\lambda_s = \frac{4}{3} \rho_s \rho_f \left(\frac{\rho_s}{\rho_f}\right) \frac{\lambda_s}{\pi} \left[9\right]
\]
Table 4: Continued

Stress strain tensor of liquid and solid phases

\[ \tau_l = \varepsilon_l u_l (V u_l + V u_l^T) - \varepsilon_l (\lambda_l + \mu_l) (V u_l) I \]

\[ \tau_s = \varepsilon_s u_s (V u_s + V u_s^T) - \varepsilon_s (\lambda_s + \mu_s) (V u_s) I \]

Collision dissipation of energy:

\[ \gamma_{\Theta_s} = \frac{121 - \varepsilon_s^3}{d_s \sqrt{\pi}} p_s e_s^2 \Theta_s^3 \]

Equation for granular temperature [10]

\[ \frac{1}{2} \left( \varepsilon_s \rho_s \Theta_s + \varepsilon_s \rho_s \Theta_s^3 + \varepsilon_s (\lambda_s + \mu_s) \Theta_s \right) = (-P_s I + \tau_s) - \varepsilon_s (\lambda_s + \mu_s) \Theta_s - 3 \varepsilon_s \rho_s \Theta_s^3 \]

Shear force at the wall:

\[ \tau_w = \frac{-n p_e \sqrt{\gamma_{\Theta_s}}}{6 e_{s, \max}} \Theta_s, \rho_s \]

Granular temperature at the wall:

\[ q_s = -\tau_s u_s, \rho_s - \frac{\sqrt{\gamma_{\Theta_s}}}{4 e_{s, \max}} (1 - \varepsilon_s^2) p_s e_s \Theta_s^3 \]

Fig. 3(a): The volume fraction pet in the reactor by Exp. 4 (X1=0.593) at (Uw=0.0178m/s)

Fig. 3(b): The volume fraction glass in the reactor by Exp. 4 (X1=0.593) at (Uw=0.0178m/s)

Fig. 3(c): Meshes generation in the reactor
RESULTS AND DISCUSSION

Overall Voidage: The predicted overall voidage values of binary particle mixtures of selected five experiments at different superficial liquid velocities have been compared with the Asif experimental data [1] in Figures 4 to 8. It can be observed that the predicted values from the present CFD simulations are in good agreement with the experimental data. The predicted values from the property average model and serial model [14] are also shown in Figures 4 to 8. Since the serial model is based on the assumption of complete segregation of the two components, it over predicts the average voidage of the bed. On the other hand, average model predicts the overall voidage with an error of 10 to 25% in comparison of 5-10% error of CFD simulation. Further, it may be pointed out that these models cannot give any qualitative or quantitative information about the concentration profiles individual solid species along the expanded bed height. Therefore, they have limitations in quantification of the segregation and intermixing characteristics of the binary solid-liquid fluidized beds.

Bed Expansion: Figure 9 shows the Overall voidage at various times up to steady state condition in the reactor for Exp. 4 ($X_1=0.394$) at superficial water velocity of 0.0178 m/s obtained from the simulation. As shown in the figure, bed expansion ascend in the column reactor to reach steady state, therefore height of bed became constant, that is agreement with experimental result completely.

Figure 10 shows the volume fraction of pet at various superficial water velocities in the reactor for Exp. 5 ($X_1=0.593$) at steady state conditions (after 50s) obtained from the simulation.
Fig. 7: Comparison of predicted average voidage values of binary particle mixtures Exp-6 (X = 0.744) at different superficial liquid velocities with the experimental values, average model and series model.

Fig. 8: Comparison of predicted average voidage values of binary particle mixtures Exp-8 (X = 0.745) at different superficial liquid velocities with the experimental values, average model and series model.

Fig. 9: The overall voidage at superficial water velocity of 0.0178 m/s in the reactor for Exp. 5 (X = 0.593).
Fig. 10: The volume fraction of pet at various superficial water velocities in the reactor for Exp. 5 (X = 0.593) at steady state conditions (after 50 s)

from the simulation. As shown in this figure, bed expansion increased in the column reactor by increasing superficial water velocity. It was concluded that the simulated data were in good agreement with the experimental ones obtained from the literature.

CONCLUSIONS

The Eulerian CFD 2D simulations based on FLUENT software are developed for water fluidization of binary mixture of glass and pet. The simulation results showed that overall bed voidage was generally in good qualitatively and reasonable quantitatively agreement with experimental data. The CFD model predicts the overall bed voidage within 5-10% in comparison with the experimental data in the range of fluidization velocities investigated; whereas, average model predicts the overall voidage with an error of 10 to 25%. The results of bed expansion prediction provided evidence that CFD simulation were in agreement with previous experimental data.

Nomenclature:

C_D Drag coefficient, [dimensionless] 
U Velocity, (m/s) 
P Pressure, (Pa) 
g Gravitational acceleration, (m/s^2) 
k Interphase exchange coefficient, [dimensionless] 
d Diameter, (m) 
Re Reynolds number, [dimensionless] 
k_{e} Diffusion coefficient for granular energy, [dimensionless] 
g_r Radial distribution coefficient, [dimensionless] 
\epsilon Coefficient of restitution for particle-particle interaction, [dimensionless] 
\epsilon_w Coefficient of restitution for particle-wall interaction, [dimensionless]

Greek Symbols:

\epsilon Volume fraction, [dimensionless] 
\rho Density, (kg/m^3) 
\tau_i Tress tensor,(Pa) 
\mu Shear viscosity, (Pa.s) 
\gamma_v Collision dissipation of energy, (kg/s m) 
I Stress tensor, [dimensionless] 
\Theta Granular temperature, (m^2/s) 
\varphi secularity coefficient, [dimensionless]

Subscripts:

l Liquid phase 
s Solid phase 
col Collision 
fr Friction 
kin Kinetic 
q Either liquid or solid phase, 
W Wall

REFERENCES


