CFD Modelling of Gas-Solids Flow in an Internally Circulating Fluidized Bed

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Abstract
This paper presents a numerical study of gas and solids flow in an Internally Circulating fluidized bed (ICFB). The gas and solid dynamics has been calculated using the commercial computational fluid dynamics (CFD) software package ANSYS/Fluent and an Eulerian-Eulerian model (EEM) with kinetic theory of granular flow used to calculate solid stresses. A two dimensional geometry was used to represent key parts of a laboratory ICFB. Simulations were conducted to assess the effect of changes to four design or operating parameters: gas distributor plate angles, presence of a heat exchange tube bundle, superficial fluidizing velocities and initial solid packing heights. The mechanism governing the solid recirculation in an ICFB has been explained based on gas and solids dynamics obtained from the simulations and the effect of the four design or operating parameters is quantified in terms of solids recirculation rate (SRR). Both of the investigated operating parameters, superficial fluidizing velocities and initial solids packing height, strongly affect solids circulation rate. For the two investigated design parameters, the presence of a tube bundle reduced the solids recirculation rate by 20%, while an inclination angle of 1.5 degree does not affect the solids recirculation rate significantly.

Keywords: internally circulating fluidized bed (ICFB), computational fluid dynamics (CFD), gas solid flow, Eulerian-Eulerian model, solid recirculation rate

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1. Introduction

An internally circulating fluidized bed (ICFB) is a type of fluidized bed with a centrally located draft tube or a plate that divides the bed into two or more sections and thus promotes solids circulation within a single vessel [1][2]. ICFBs have several advantages over conventional circulating fluidized beds (CFBs), such as reduced height and construction costs, compact size and comparatively small heat loss from the reactor. Therefore, ICFBs have been widely used for various processes, such as coal combustion, coal gasification, incineration of solid wastes, continuous adsorption and desorption and desulfurization. Despite being an intensive research area, there are no design rules or correlations that can be used to quantitatively predict the solids recirculation rate in a specific system because it is affected by so many factors, such as the height of the baffle, height of initial packed solids, bed cross-sectional area, orifice size, distributor geometry, gas velocities, presence of internals, as well as gas and solid properties [3][4].

Detailed investigation of gas-solids flow using an industrial scale ICFB is very difficult, if not impossible, because they often operate at high temperatures, and mostly involve chemical reactions or combustion making detailed measurements very difficult. Furthermore, the ability to trial unusual operating conditions is constrained by the need to maintain control over the unit operation. Physical and numerical models are often used to optimise design and/or operating conditions, and provide the ability to trial changes to operating conditions and geometrical configurations without risk.

Solids recirculation rates (SRR) are obtained from cold small scale physical models by using a range of methods such as multi-fibre optical probes [5], radiotracer particles [6] and hot tracer techniques [7][8]. There is a risk in using the cold model data for designing plant scale operation, as cold models often use different solid and gas properties from the hot system. Pilot scale trials are often a further step before a commercial scale unit can be built, but scale-up problems can still be experienced.
CFD modelling can account for these complexities and use the actual fluid properties with chemical reactions, thus a wide range of variations in physical design and operational parameters can be tested and refined until a design that gives optimum performance is identified. Over the past one to two decades, with advances in computing speed and parallelisation technology, improved software and multiphase algorithms, CFD has progressed substantially to a point where it can be used for prediction of complex multiphase flows such as those encountered in an ICFB. Today, CFD models play an increasingly important role in process design, control and/or optimisation of complex multiphase systems [9].

This paper presents a study undertaken using CFD modeling of gas-solid flow in an ICFB (Figure 1). The ICFB is used to separate the reaction chamber (RX) from a heat recovery chamber (HEX). In this case, the solid particles pass through the fluidized bed reaction chamber and are then circulated into a separate fluidized bed heat exchange chamber where they are cooled or heated in order to regulate the bed temperature. A two fluid model or more correctly an Eulerian-Eulerian model (EEM) incorporating the kinetic theory of granular flow [10] [11] is selected as the modeling technique and the CFD package ANSYS/Fluent is the numerical platform [12] used in the study. Four design or operating parameters are investigated: gas distributor plate angles, presence of a heat exchanger bundle, superficial fluidizing velocities and initial solid packing heights. Following a detailed investigation of the mechanisms governing the solid recirculation, the effect of the four design or operating parameters is quantified in terms of solid recirculation rate (SRR).

2. CFD Model Description

2.1 Model description

Depending on the application and information required, gas-solid flow can be modeled at different length scales: at the particle scale or at the macro level by local averaging. The particle scale approach
tracks the motion of individual particles using a discrete element method (DEM), and the flow of gas using a continuum based CFD model with local properties averaged over a number of computational cells. This approach results in what is commonly referred to as a DEM-CFD model in the literature [13][14][15]. The macro level approach treats both solid and gas phase as interpenetrating continua, the motion of each phase is solved using a continuum based CFD model with suitable closure terms. This method is known as the Eulerian-Eulerian model [10][11]. DEM-CFD models can predict detailed solid flow behaviour [16], but are very computational demanding. EEMs take relatively less computational time, but their accuracy depends on the closure model used to describe properties such as solids viscosity and solids pressure. In this work the kinetic theory of granular flow is used for these closures. The former model is suitable for fundamental research, while the latter for process design. Both models are widely used to study various gas-solid flow behaviour and are areas of ongoing research at CSIRO [17][18][19][20]. In this study, the EEM is adopted to undertake an investigation of the parameters of interest.

The governing equations solved in this work are summarized in Table 1 and are an extension of the single phase Navier-Stokes equations to multiphase systems. These equations describe conservation of mass and momentum for each phase as well as the conservation of fluctuating translational kinetic of the solid phase based on the kinetic theory of granular flow. Gidaspow [10] described the kinetic theory of granular flow and how it is applied to the solids phase to enable calculation of solids phase pressure and viscosity. A summary of the sub-models used in this work and additional equations required to close the governing equations are given in Table 2. Values used for parameters in the models are: maximum solids volume fraction \( \alpha_{s,\text{max}} \) is set to 0.62, a value of 0.9 [11] is used for the restitution coefficient \( e \) and for the frictional stress model an internal friction angle \( \phi \) of 30° is used.

ANSYS/Fluent [12] is used to solve the model equations given in Table 1 by a finite volume method using the “phase couple SIMPLE” algorithm to handle pressure-velocity and phase coupling. A second
order discretisation scheme is used for convection terms in the momentum equations while the QUICK scheme is used for the volume fraction equations. A time step of 0.001 seconds is used to advance the solution in time, with a second order implicit time integration scheme. The model is well documented in the literature [10] and fully implemented in ANSYS/Fluent [12] and widely used in fluidized bed study [21], readers wanting further details of the numerical model are referred to the various references listed.

It is worth noting that the EEM model has been further developed by various researchers, for example to include the use of a continuous stitching function to smoothly bridge the solid stresses from the viscous to the plastic regime in a spouting bed [25], modification of the drag law for size segregation study of binary systems [26], extension of kinetic theory to multiple particle sizes [27]. Recently, DEM type of model has been used to build continuum process models for granular flow systems [28], but this is still in an early stage for fluidized bed systems [29]. This study is simply based on the available model implemented in ANSYS/Fluent.

2.2 Simulation conditions

Figure 1 shows the different geometries used in this work, which are two dimensional fluidized beds, representing part of an ICFB reactor. The reactor has two inter-connected fluidized bed chambers, with the left chamber representing the “reaction chamber” (RX), and right chamber representing the heat exchanger chamber (HEX). The two chambers are separated by a vertical baffle with a slot in the lower section to enable the return of solids from the HEX to RX. The slot height is 25 mm and the height of the top of the baffle from the distributor is 275 mm. The baffle thickness is 8 mm. Table 3 lists the physical properties of gas and solid particles.

Hexahedra cells are used to mesh the geometries, in the case of Figure 1a 30 uniform cells are used across the width of both the RX and HEX chambers while two cells are used across the baffle width. Vertically four cells are used across the 25mm slot under the baffle and 30 along the baffle’s height,
another 50 cells are used in the freeboard above the baffle giving a total of 5148 cells in the model. Similar mesh resolutions were used in the other two geometries.

Table 4 lists the simulation conditions for this study. A base geometry as shown in Figure 1a is used to investigate the effect of two operating parameters: superficial fluidizing velocity in the RX ($U_f$) and initial solid packing height. The effect of $U_f$ is investigated when the initial solid packing height is set to 275 mm, the same as the baffle height, and the superficial fluidizing velocity in the HEX ($U_m$) is set 0.12 m $s^{-1}$, which is about 4.3 times of the minimum fluidization velocity ($U_{mf}$, 0.028 m $s^{-1}$). The effect of solids packing height is investigated with $U_f$ and $U_m$ held constant, while the bed height is set to 60%, 80%, 100% and 120% of the baffle height. Figure 1b shows the geometry for the investigation into the effect of gas distributor inclination angle. The angle is set 1.5 degree with the RX chamber deeper than the HEX chamber and the slot height is kept to 25 mm. Figure 1c shows the geometry used to investigate the effect of a tube bundle that is mounted in the HEX chamber. In the investigation of the effect of a gas distributor angle and a tube bundle, simulations are conducted with constant $U_f$ (0.30 m $s^{-1}$), $U_m$ (0.12 m $s^{-1}$) and initial solid bed height (275 mm). Gas enters the base of the ICFB through two distributors; the velocity through each is constant at $U_f$ and $U_m$. The simulation was conducted using ANSYS/Fluent and the simulation data is processed using ANSYS/CFD-Post.

It is worth noting that the main purpose of this study is to explore the likely effect of different designs and operating parameters on the bed behavior and solids circulation rate. A two dimensional geometry is selected to reduce computational time. The 2D simulations might not fully represent the actual case, as most of real applications are three dimensional. However, for practical applications the trends predicted would be similar and 2D simulations are acceptable for proof-of-concept designs and for screening a larger number of design options than is possible with 3D models. To quantify the differences between 2D and 3D simulations work is currently underway and will be discussed in a later publication.
3. Results and Discussion

3.1 Gas and solid flow dynamics

Figure 2 shows the instantaneous spatial distributions of solid volume fraction (Figure 2a), pressure (Figure 2b), solid and gas velocity vectors (Figure 2c,d) at a simulation time of 19.7 seconds, with the simulation parameters $U_t=0.60 \text{ m s}^{-1}$, $U_m=0.12 \text{ m s}^{-1}$, and initial packing height 275 mm. The central baffle divides the bed into two separated fluidized beds, where each part is mainly affected by the gas injection velocity through the local distributor. As shown in Figure 2a, the fluidization is much stronger in the RX chamber than that in HEX chamber, as is demonstrated by bubble size and bed expansion height. For a fluidized bed system, the bed pressure is closely related to solid volume fraction, or dynamic solids holdup. The solids hold-up in the HEX chamber is higher than that in the RX chamber. Correspondingly, the pressure in HEX chamber is higher than that in RX chamber as shown in Figure 2b. The pressure difference between HEX and RX provides a driving force for solid and gas flow from HEX to RX chamber through the bottom slot, as is evidenced by Figure 2c and 2d. Above the baffle, strong fluidization in the RX chamber disperses solids to HEX chamber. Thus, the cause of solid circulation in an ICFB is well explained by these results. This typical behavior applies to other cases in this study, hence such details are not discussed further.

Solid particles flowing from the RX to HEX chamber above the baffle and from the HEX to RX chamber through the bottom slot also affect the gas flow significantly. This effect of the baffle makes the gas-solid flow quite different from conventional bubbling fluidized beds. Figure 3 shows snapshots of the solid flow pattern and gas streamlines at different instants in time. Flow in the HEX chamber is characterized by strong local recirculation and bypassing of gas from the HEX to RX chamber through the slot. In the RX chamber, the streamlines indicate a strong channeling flow with less recirculation. Above the baffle, the flow of gas deviates towards the HEX side, as an effect of more vigorous bubbling.
fluidization of the RX and a greater amount of solids being thrown into the freeboard than occurs from the HEX side [30].

Figure 4 plots the variation of solids flux and gas bypass rate with time. The solids flux is calculated as the total solid circulation rate divided by the cross-sectional area of the HEX chamber. The solid flux varies strongly with time. Figure 4 also plots the gas bypass rate through the slot, which fluctuates in a similar manner to the solid flux: a higher instantaneous solids flux often corresponds to a higher gas bypass rate.

Figure 5 plots the bed pressure near the gas distributor, which is expressed as an averaged value over the HEX and RX chambers respectively. For most of the time, the pressure in the HEX chamber is higher than that in the RX chamber, which provides the driving force for solid and gas flow from the HEX to RX chamber through the slot. Consistent with the solid flow pattern shown in Figures 2 and 3, the pressure fluctuation in the RX chamber is much higher than that in the HEX chamber, as a result of the stronger fluidization in the RX chamber. Occasionally, the bed pressure is higher in the RX chamber. However, there is no observation of reverse flow from the RX to the HEX chamber through slot. It is likely that the pressure reversal does not exist for sufficiently long periods of time to reverse the gas-solids flow, given the dynamic response time of the solids. Another possible reason could be that the pressure is averaged over the distributor. Further investigation by plotting pressures near the slot may better explain this.

3.2 Effect of the $U_f$

The effect of $U_f$ on overall SRR is shown in Figure 6 where the mean solids circulation rate is plotted as a function of different ratios between $U_f$ and $U_m$, expressed as $(U_f-U_{mf})/(U_m-U_{mf})$. A time-averaged value of the last 15 seconds of the total 20 seconds of simulation time is used for this quantification. The solid flux increases as the ratio increases over the investigated range, but the rate of increase is
decreasing. The trend is consistent with previous experimental findings [3][4][8], but a detailed quantitative comparison cannot be made because geometrical and operating parameters for the cases are different.

Figure 7 plots mean pressure near the gas distributor in both the RX and HEX chambers. The value increases in the HEX chamber and reduces in the RX chamber as velocity $U_f$ is increased. The pressure difference between the chambers is plotted in Figure 8, where a similar trend to Figure 6 is observed. The correlation between pressure difference and solid flux rate is plotted in Figure 9. It is interesting to see that the relationship is almost linear.

### 3.3 Effect of solids packing height

The initial packing height of the bed strongly affects the solids recirculation rate. When the initial packing height is low, fast fluidization in the RX chamber may be simply below the baffle height, thus no solids flow across the top of the baffle from the RX to HEX chamber. This leads to no solid recirculation between the two chambers. It is of interest to know how the SRR is affected by initial solids packing height. It is expected that the effect of initial packing height varies for different ratios of $U_f$ to $U_m$. For this initial investigation, $U_f$ is set 0.30 m s$^{-1}$. It is also interesting to check whether there is still an effect when the packing height is above baffle height. Thus, four packing height are selected for this comparison, which are 60%, 80%, 100%, 120% of the baffle height.

Figure 10 shows the SRR at different initial solids packing heights. At this set of $U_f$ and $U_m$, when the initial solids packing height is less than the baffle height, the solids circulation rate increases as the initial packing height increases, and the rate of increase decreases. It is interesting to see that when the initial packing height is larger than the baffle height, the SRR reduces. When the initial packing height is above the baffle, there will be more solids maintained in the fluidized state above the baffle in both RX and HEX chambers. Thus, the pressure difference between the RX and HEX chamber will be
reduced. Consequently, the SRR reduces. The results demonstrate that the baffle is the key to introducing and controlling solids recirculation. It is likely that an initial packing of 100% of baffle height might not correspond to the maximum SRR under current operating velocity. Also, the initial packing corresponding to a maximum SRR is dependent on operating velocities to some extent. To obtain a full picture of the relationship, more parametric studies are required beyond the general proof-of-concept study given in this paper.

3.4 Effect of a heat exchanger tube bundle

Tube bundles are often mounted in gas fluidized beds for applications in petroleum or chemical reactors and electric power boilers to control the heat transfer and/or reaction rate. In addition to the investigation of heat transfer [31][32], the implementation of internals has been reported to affect gas and solid flow significantly, such as axial mixing [33], bubble size [34], size segregation [35].

For the present ICFB design, a tube bundle is fitted in the heat exchanger chamber to provide control of the reacting temperature. Presumably the tube bundle will reduce solid recirculation rate due to the frictional resistance between solids and wall of tubes. It is interesting to know the extent of its effect, as it is a key concern for this design. Figure 11 shows the solids recirculation rate with and without a tube bundle. As is expected, the presence of a tube bundle reduces solids recirculation, probably due to the resistance of tube bundle on gas and solid motion. For the present designed tube bundle, solids recirculation rate decreases by about 20%, demonstrating that the current tube bundle has a significant effect on the SRR in the ICFB.

3.5 Effect of gas distributor plate angle

For the ICFB design, the gas distributor plate is inclined at an angle for the purpose of increasing solids discharge from the reactor and to promote solid movement above the gas distributor plate. This design is essential to avoid solid accretions forming near the plate in systems with high temperatures and solid
particles that can soften or melt. It is again interesting to know if this angle is likely to have an effect on solids recirculation rate. An inclination angle of 1.5 degree is selected for this test (Figure 1b). Figure 12 shows the calculated solids recirculation rate for cases with and without an inclined angle distributor plate. The SRR increases by 3% when the gas distributor is inclined 1.5°, indicating the effect is not significant.

4. Conclusions

Complex gas and solids flow in an ICFB solid circulation system has been investigated using an EEM with the incorporation of the kinetic theory of granular flow. The effect of two operating parameters (superficial fluidizing velocity in the RX chamber and the initial solids packing height) and two design parameters (presents of a tube bundle in HEX chamber and an inclined angle for gas distributor plate) is assessed based on numerical results obtained using the commercial CFD software package, ANSYS/Fluent. The simulation results demonstrate that the present CFD model can capture the key features of an ICFB system, fast fluidization in the RX chamber, bubbling fluidization in the HEX chamber and solids circulation between the chambers. The mechanisms governing solids circulation in an ICFB have been well explained based on gas and solids dynamics obtained from simulations. Results show the pressure difference between the HEX and RX chamber drives the solid flow from HEX to RX through a slot, and the solid is dispersed above baffle from the RX to HEX chamber.

Both of the investigated operating parameters, \( U_f \) and initial solids packing height, strongly affect solids circulation rate. For the investigated ratio of \( U_f \) to \( U_m \), the solid flux increases as the ratio increases, and the rate of increase decreases. When the initial solids packing height is less than the baffle height, the solids flux increases as the initial packing height increases, while the rate of increase decreases. When the initial packing height is larger than the baffle height, the solid flux reduces, demonstrating that the baffle is the key to introducing and controlling solid recirculation.
For the two investigated design parameters, the presence of a tube bundle reduced the solids recirculation rate by 20%, while an inclination angle of 1.5 degree does not affect the solids recirculation rate significantly.

Acknowledgements

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Nomenclature

- $d_p$: particle diameter
- $e$: coefficient of restitution
- $g_0$: radial distribution function
- $g$: gravity vector
- $I$: identity tensor
- $p$: pressure
- $P_c$: critical solids pressure
- $P_s$: solids pressure
- $Re$: particle Reynolds number
- $t$: time
- $u$: velocity vector
- $U_m$: gas superficial velocity in HEX chamber
- $U_f$: gas superficial velocity in RX chamber
- $U_{mf}$: minimum fluidization velocity
- $\alpha$: volume fraction
- $\alpha_{s,max}$: maximum solids volume fraction
- $\beta$: interphase momentum transfer coefficient
- $\gamma$: collisional dissipation of solid fluctuating kinetic energy.
- $\phi$: internal friction angle
- $\mu$: shear viscosity
- $\kappa$: granular conductivity
- $\theta$: granular temperature
- $\rho$: density
- $\sigma_s$: solids stress tensor
- $\zeta$: bulk viscosity
\textit{subscripts}

\begin{itemize}
\item \textit{g} \quad \text{gas phase} \\
\item \textit{s} \quad \text{solids phase} \\
\item \textit{s,c} \quad \text{solids collision} \\
\item \textit{s,k} \quad \text{solids kinetic} \\
\item \textit{s,f} \quad \text{solids frictional}
\end{itemize}

\textbf{References}


Table 1. Eulerian-Eulerian model equations for gas-solid flow

Phase Mass Conservation Equations

\[ \frac{\partial (\alpha, \rho_g)}{\partial t} + \nabla \cdot \left( \alpha, \rho_g u_g \right) = 0 \]

\[ \frac{\partial (\alpha, \rho_s)}{\partial t} + \nabla \cdot \left( \alpha, \rho_s u_s \right) = 0 \]

Momentum Conservation Equations

\[ \frac{\partial (\alpha, \rho_g, u_g)}{\partial t} + \nabla \cdot \left[ \alpha, \rho_g u_g \otimes u_g - \alpha, \mu_s \left( \nabla u_g + \left( \nabla u_g \right)^T \right) \right] = -\alpha, \nabla p + \beta (u_g - u_s) + \alpha, \rho_s g \]

\[ \frac{\partial (\alpha, \rho_s, u_s)}{\partial t} + \nabla \cdot \left[ \alpha, \rho_s u_s \otimes u_s \right] = -\alpha, \nabla p + \beta (u_s - u_s) + \alpha, \rho_s g + \nabla \sigma \]

Granular Kinetic Energy Conservation Equation

\[ \frac{3}{2} \left[ \frac{\partial (\alpha, \rho_s, \theta)}{\partial t} + \nabla \cdot \left( \alpha, \rho_s u_s, \theta \right) \right] = \sigma \cdot \nabla u_s - \nabla \cdot \left( -k \nabla \theta \right) - \gamma \]
Table 2. Constitutive Relationships for Eulerian-Eulerian model for gas-solid flow

Inter-phase momentum transfer [10]

\[
\beta = 150 \left( \frac{1 - \alpha_g}{\alpha_g} \right) \mu_e + 1.75 \frac{\rho_s |\mathbf{u}_e - \mathbf{u}_g| (1 - \alpha_g)}{d_p} \quad \text{for } \alpha_g < 0.8
\]

\[
\beta = \frac{3}{4} C_d \rho_s |\mathbf{u}_e - \mathbf{u}_g| (1 - \alpha_g) \alpha_g^{2.65} \quad \text{for } \alpha_g \geq 0.8
\]

where

\[
C_d = \begin{cases}
24 \frac{(1 + 0.15 \text{Re}^{0.67})}{\text{Re}} & \text{Re} \leq 1000 \\
0.44 & \text{Re} > 1000
\end{cases}
\]

and

\[
\text{Re} = \frac{\rho_s |\mathbf{u}_e - \mathbf{u}_g| \alpha_g d_p}{\mu_e}
\]

Solids Stress

\[
\sigma_s = \left[ - P_s + \zeta \mathbf{V} \cdot \mathbf{u}_s \right] \mathbf{I} + 2\mu_s \mathbf{S}_s
\]

\[
\mathbf{S}_s = \frac{1}{2} \left[ \mathbf{V} \mathbf{u}_s + (\mathbf{V} \mathbf{u}_s)^\top - \frac{1}{3} \mathbf{V} \cdot \mathbf{u}_s \mathbf{I} \right]
\]

Solids Pressure [22] [23]

\[
P_s = \rho_s \alpha_s \left[ 1 + 2(1 + e) \alpha_s \eta_s \right] + P_e
\]

\[
P_e = \begin{cases}
10^5 \left( \alpha_s - \alpha_{s_{\text{max}}} \right)^{10} & \alpha_s > \alpha_{s_{\text{max}}} \\
0 & \alpha_s \leq \alpha_{s_{\text{max}}}
\end{cases}
\]

Solids shear viscosity [22] [24]

\[
\mu_s = \mu_{s_x} + \mu_{s_x} + \mu_{s_f}
\]

\[
\mu_{s_x} = \frac{4}{5} \alpha_s^2 \rho_s d_p \eta_s (1 + e) \left( \frac{\theta \eta}{\pi} \right)^{\frac{1}{2}}
\]

\[
\mu_{s_f} = \frac{\alpha_s \rho_s d_p \sqrt{\eta \pi}}{6(3 - e)} \left[ 1 + \frac{2}{5} (1 + e)(3e - 1) \alpha_s \eta_s \right]
\]

\[
\mu_{s_f} = \frac{P_s \sin \phi}{2 \sqrt{3} \mathbf{S}_s : \mathbf{S}_s}
\]

Solids bulk viscosity [23]

\[
\zeta_s = \frac{4}{3} \alpha_s^2 \rho_s d_p \eta_s (1 + e) \left( \frac{\theta \eta}{\pi} \right)^{\frac{1}{2}}
\]

Granular conductivity [22]

\[
\kappa = \frac{15 \alpha_s \rho_s d_p \sqrt{\eta \theta}}{4(41 - 33\eta)} \left[ 1 + \frac{12}{5} (4\eta - 3) \alpha_s \eta_s + \frac{16}{15\pi} (41 - 33\eta) \eta_s \alpha_s \eta_s \right]
\]
where $\eta = \frac{1}{2}(1 + e)$

**Collision energy dissipation** [23]

$$\gamma = \frac{12(1-e^2) \rho_s g_s}{d_s \sqrt{\pi}} \alpha_s^2 \theta^{\frac{3}{2}}$$

**Radial distribution function** [23]

$$g_n = \left[ 1 - \left( \frac{\alpha_n}{\alpha_{n,\max}} \right)^{\frac{3}{2}} \right]^{\frac{1}{2}}$$

---

### Table 3. Gas and solid properties

<table>
<thead>
<tr>
<th>Solid density</th>
<th>2760 [kg m$^{-3}$]</th>
<th>Gas density</th>
<th>0.585 [kg m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid diameter</td>
<td>0.0003 [m]</td>
<td>Gas viscosity</td>
<td>$5.12 \times 10^{-5}$ [Pa s]</td>
</tr>
<tr>
<td>$U_{mf}$</td>
<td>0.028 [m s$^{-1}$]</td>
<td>Initial gas porosity</td>
<td>0.38</td>
</tr>
</tbody>
</table>

### Table 4. Simulation conditions

<table>
<thead>
<tr>
<th>Effect of $U_r$</th>
<th>$U_r$ [m s$^{-1}$]</th>
<th>$U_m$ [m s$^{-1}$]</th>
<th>Initial solid packing height [mm]</th>
<th>Gas distributor inclined angle [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of $U_r$</td>
<td>0.24, 0.30, 0.40, 0.60</td>
<td>0.12</td>
<td>275</td>
<td>0</td>
</tr>
<tr>
<td>Effect of solid packing height</td>
<td>0.30</td>
<td>0.12</td>
<td>165, 220, 275, 330</td>
<td>0</td>
</tr>
<tr>
<td>Effect of gas distributor angle</td>
<td>0.30</td>
<td>0.12</td>
<td>275</td>
<td>0, 1.5</td>
</tr>
<tr>
<td>Effect of presence of a heat exchanger buddle</td>
<td>0.30</td>
<td>0.12</td>
<td>275</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 1. Schematic diagram of the 2D ICFB geometry: (a) base case; (b) the angle of gas distributor plate is 1.5 degree; (c) presence of a tube bundle in HEX chamber. The unit of dimension is in millimeter, and the tube diameter is 12.7 mm.
Figure 2. Spatial distribution of gas and solid particles for the simulation case ($U_t=0.60 \text{ m s}^{-1}$, $U_m=0.12 \text{ m s}^{-1}$, and initial packing height 275 mm) when the simulation time is 19.7 second: (a) solid volume fraction; (b) bed pressure; (c) solids velocity; (d) gas velocity.
Figure 3. Snapshots of solid volume fraction distribution and gas streamlines at different times for the simulation case ($U_f=0.60$ m s$^{-1}$, $U_m=0.12$ m s$^{-1}$, and initial packing height 275 mm).
Figure 4. Variation of solid circulation and gas bypass rate with time

Figure 5. Variation of mean bed pressure at distributor of the HEX and RX with time
Figure 6. Effect of $U_f$ on solid recirculation rate

Figure 7. Effect of $U_f$ on bed pressure of the RX and HEX chambers near distributor

Figure 8. Effect of $U_f$ on pressure difference between HEX and RX chambers
Figure 9. Correlation of solid recirculation rate as a function of pressure difference between HEX and RX

Figure 10. Effect of initial solids packing height on solid recirculation rate
Figure 11. Effect of heat exchanger tube bundle on solids recirculation rate for the simulation parameters: \( U_f = 0.30 \text{ m/s}, \ U_m = 0.12 \text{ m/s}, \) and initial packing height 275 mm.

Figure 12. Effect of gas distributor incline angle on solids recirculation rate for the simulation parameters: \( U_f = 0.30 \text{ m/s}, \ U_m = 0.12 \text{ m/s}, \) and initial packing height 275 mm.