A one-dimensional model of gas-solids flows in the acceleration zone of a CFB riser

Chao Zhu, Jun You

Mechanical Engineering Department, New Jersey Institute of Technology, Newark, NJ, 07102

Abstract

In the lower part of a circulating fluidized bed (CFB) riser, the solids are accelerated towards a fully developed state. Understanding on hydrodynamic behaviors of solids in the acceleration zone is particularly important due to the high solids holdup and long solids residence time as well as the dramatic variations in solids concentration, velocity and pressure drop within this zone. While many studies on the axial solid flow structure have been reported, almost all of them are based on the assumption of fully developed flows where the pressure gradients are completely converted to the axial distribution of solids concentrations. However, as shown by our model predictions, the pressure drop due to the solid acceleration in the acceleration zone is far more than negligible, compared to the pressure drop for the solids concentration. In addition, the pressure drop due to energy dissipation from inter-particle collisions, particle-wall frictions, and gas-solids friction also plays an important role when solids concentration is high.

In this paper, a one-dimensional model has been developed to characterize the pressure drop partitions among solids concentration, solids acceleration, and energy loss in the acceleration zone in a CFB riser. The axial distributions of solid velocity and solid concentration are obtained by solving the equations. Consequently effects of solids acceleration and energy loss on the axial distributions of solids velocity and concentration are illustrated.

1. Introduction

Circulating fluidized beds (CFB) nowadays find a wide-spread aplication in a variety of industrial processes such as coal combustion and coal gasification, catalytic cracking of oil, and gas purification. Despite their widespread application the fluid mechanics of CFBs is unfortunately not very well understood, This can be attributed , on one hand, to the very complex hydrodynamics of these systems which complicates a thorough theoretical description and understanding, on the other hand, to the significant difficulties encountered in measuring local fluid mechanic properties in dense gassolid two phase flows.

As we all know, The axial voidage profile in a CFB riser is typically composed of five sections: the acceleration, developed bottom-dense, transition, top-dilute and exit sections. Usually, the acceleration and developed bottom-dense sections are together termed the bottom-dense (lower dense). With respect to reactions, heat transfer and solid handling in the CFB, the acceleration zone is of particular importance. The reasons are the relatively higher solids holdup and its strong variation along this zone as compared with the fully developed zone. Therefore, understanding the solid mixing and flow structure in the acceleration zone becomes very critical for highly exothermic reactions taking place in the CFB.

From the general physical point of view, when particles move upword in the CFB riser, there are three forces acting on a particle moving upward in a swarm of other particles in the riser, as shown in Fig. 2. These forces are gravitational , buoyancy and fluid drag. If neglecting wall friction and acceleration forces, the pressure drop over acertain section of a riser tube can he attributed to gravity forces, according to the well-known manometer formula. This principle has been used by many investigators to measure the volume-average solids concentration.

In order to explain this phenomenon, Pugsley and Berruti [2] adopted the force-balance equation for one-dimensional motion of single particles through fluids (particle-based approach or PBA). Godfroy [3] also developed a model based on the force balance to predict hydrodynamics of CFBs. This model is also a PBA and under-predicts the acceleration zone length. P.Schlichthaerle [4] draw some inclusion of the flow structure, radial and axial profiles, based on the experiment basis and got some empiristic relations. And many others researchers have put forwarded a large number of useful results.

Unfortunately, it’s still hard to say that we already have got a clear idea about the hydrodynamics of this particular part of the CFB riser. The lack of fit and so many puzzles may be attributed to the complicated hydrodynamics of these systems that could not be explained properly with his approach.
Yet the qualitative and quantitive problems such as what the importance of different factors play in this interactive dynamics, what the percentage of pressure drop caused by acceleration, friction and collision inspectively among the total pressure drop along the CFB riser, how long the acceler ation zone is under different operating load, what the distribution of solid concentration along the axial direction, and etc, still exist there puzzling us.

However, what we must do should not slide over these important problems. Therefore, to develope a more realistic model for defining the hydrodynamics of the acceleration zone seems to be vital from the research and practical point of view. Neverthanless, what this paper going to do is present a new way to crack the hard nut confronting with us.

2. modeling results and discussion

At first we do not consider the acceleration and frictioon effect of the particle, and assume that the only contribution to the axial suspension density is the hydrostatic head of solids, which is the tradional way widely used and accepted in industrial field, then the axial suspension density and / or voidage may be related to the pressure drop through the following expression:

$$\frac{dP}{dL} = \rho_s g(1-\varepsilon)$$

if we can know the pressure drop profile based on the measurement, then the axial suspension or/ voidage can be easily calculated from above equation.

Since there are intrinsic relationship among the parameters we are interested in, the others can also been deduced by following equations:

$$u_s = \frac{G_s}{(1-\varepsilon)\rho_s}$$

So we can easily get the axial voidage and axial velocity profile based on the measurement results of pressure at certain locations along axial direction. Let's take one actual operating case as a example.

Gs=125 kg/m^2s

Ugas0= 5.7 m/s

Density of solid ρ s: 1460 kg/m^3

pipe Height Z: 14 m

The results are shown as figure 1 and 2.

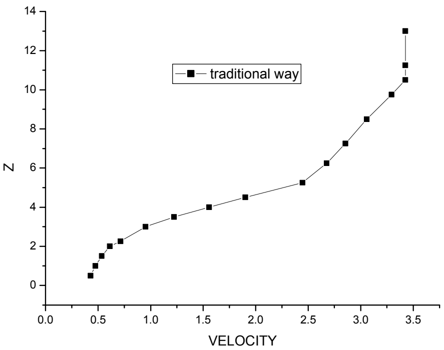


Figure 1 Velocity along z direction by traditional way

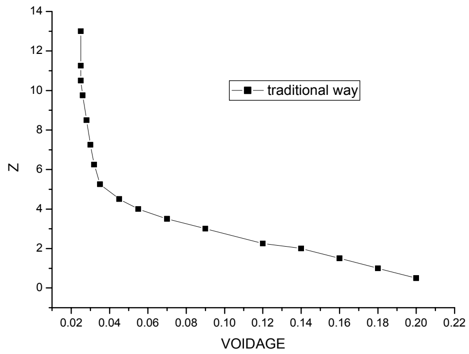


Figure 2 ASF along z direction by traditional way

Whereafter, our question is how to consier the influence coming from particle acceleration, friction and collision. In general, the flow of any gas-particle mixture in a pipe and let's take any influence into account, that is to say, no assumption has been made here. Based on the the momentum banlance, we can draw the eqation 1.

$$\begin{bmatrix} Net\ force\ acting \\ on\ pipe\ contents \end{bmatrix} = \begin{bmatrix} Rate\ of\ increase\ in \\ momentum\ of\ contents \end{bmatrix}$$

Then we can get the general expression for any gas-particle mixture in any pipe,

$$p_1 - p_2 = \underset{(1)}{\frac{1}{2}(1-\varepsilon)\rho_g U_g^2} + \underset{(2)}{\frac{1}{2}\varepsilon\rho_s U_s^2} + \underset{(3)}{F_s L} + \underset{(4)}{F_g L} + \underset{(5)}{\rho_s L\varepsilon g\sin\theta} + \underset{(6)}{\rho_g L(1-\varepsilon)g\sin\theta} \quad (1)$$

Equation (1) indicates that the total pressure drop along a straight length of pipe carrying solids in dilute phase transport is made up of a number of terms:

(1) pressure drop due to gas acceleration
(2) pressure drop due to particle acceleration
(3) pressure drop due to gas-to-wall friction
(4) pressure drop related to solid-to-wall friction
(5) pressure drop due to the static head of the solids
(6) pressure drop due to the static head of the gas

neglecting the effect from gas phase, and do some further simplication, that is;

$$-\frac{dp}{dz} = solids\ hold\_up + solid\ \ acceleration + frcitional\ loss$$

$$= \alpha_s \rho_s g + \alpha_s \rho_s u_s \frac{du_s}{dz} + f_{fc} \qquad (2)$$

$$\chi = \frac{G_s \frac{du_s}{dz}}{(-\frac{dp}{dz})}$$

define: $$\beta = \frac{f_{fc}}{(-\frac{dp}{dz})}$$

$$\delta = \frac{\alpha_s \rho_s g}{(-\frac{dp}{dz})}$$

$$\therefore \chi + \beta + \delta = 1$$

and we already have $G_s = \alpha_s \rho_s u_s$, so after rearranging the equation (2), the following equation (3) can be gotten.

$$\frac{du_s}{dz} = -\frac{\frac{dp}{dz}}{G_s} - \frac{g}{u_s} - \frac{f_{fc}}{G_s} \qquad (3)$$

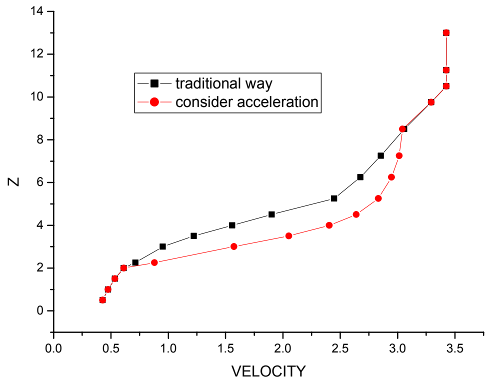
till then we can clearly understand the main factors which lead to the pressure drop are composed by three items, and apparently what the traditional way get are only the first item in equation (2), and all the other 2 item has been neglect. While as we all know the effects coming from the other two items are unneglectable, what we do here is to take into account these two factors and try to demonstrate their significance.

Let's do it step by step, firstly, let's solely consider the influence coming from particle acceleration.

What we do in our model is using Runge-Kutta 4th order way to sovle the differential equation (3). As for the mearsured pressure, the linear interpolation is used here, and the initial conditions are:

$$\alpha_0 = \frac{\frac{dp_0}{dz}}{\rho_s g}, \text{ and } \left. u_{s0} = \frac{G_s g}{\frac{dp_0}{dL}} \right|_{z=0.5m}$$

Hopefully the satisfying results can be reached from calculation.



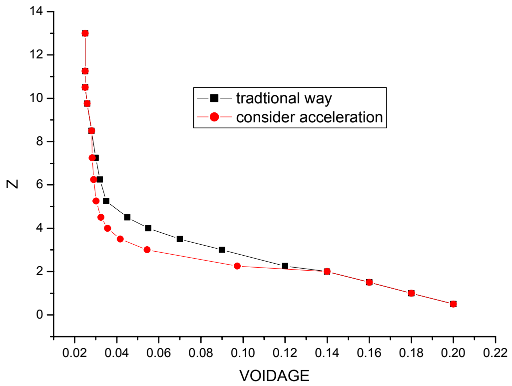


Figure 3 velocity along z direction when considering acceleration **Figure 4 ASF along z direction when considering acceleration**

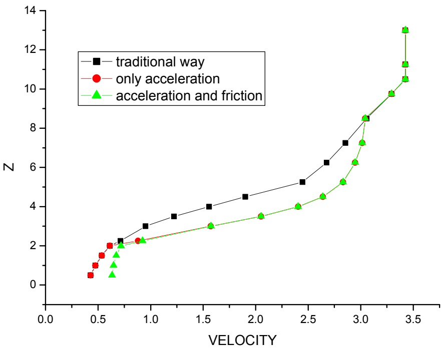
Based on the comparision of the two ways, it illustrated that at the range of beginning and end of the transport, the two models can agree with each other quite well. However in the middle part, we can see the voidage is overestimated, and the particle velocity is underestimated also to some degree, the reason for this divergence is other factors leading to the pressure drop are neglected during the calculation. As for the quantitive results we will discusse as follows.

Regrading with the friction and collision effect, we use a friction coefficient to correct our result. The way to determine the correct cofficient are based on some boundary conditions and experiential datum.

The correct curve is;

$$C = 0.068 - 2.88\alpha + 33.6\alpha^2 - 64\alpha^3 \qquad (4)$$

and we get the related result are illustrated in figure 4, 5



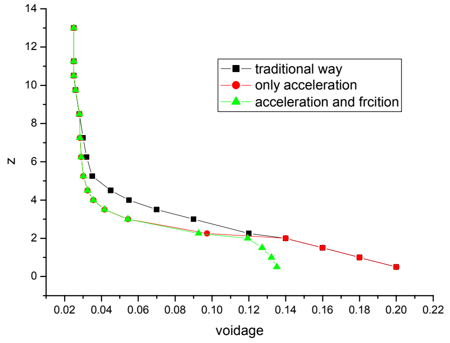


Figure 4 Velocity along z direction when consider acceleration and friction

Figure 5 ASF along z direction when consider acceleration and friction

The quantitative effect from acceleration can be easily estimated after all the relevant calculations have been done. From the figure 6, when the solid voilage exceed 0.14, the solid acceleration influence (χ) can be neglected, furthermore, the influence reach its maximum value, approximatly 0.4, when solid voidage is about 0.065. Besides this point, its influcence became smaller with voidage increasing or decreasing, which can be obvisouly observed from figure 6. In figure 7, the influence of the friction and collision has been demonstrated. From the curve we know, when solid voidage is smaller than 0.09 or less, the influence is quite small and neglectable. However with the increasing of solid voidage, the influence is also becoming stronger. According to our calculation and actual industrial experience, this influence percentage (β)can reach up to 0.35 when solid is dense enough. It is realized that if we don't take this factor into account in dense phase range, the error will be remarkable. So this result also give explainlation to the invalid of the tradition way shown in the begin of this article.

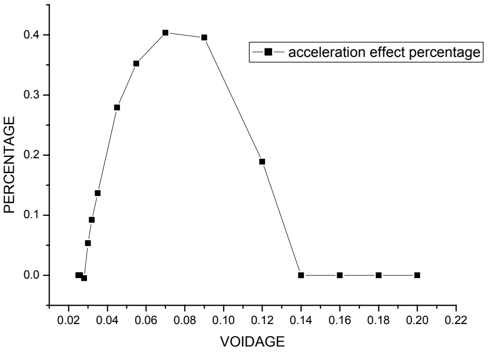


Figure 6 Acceleration effect percentage when consider acceleration only

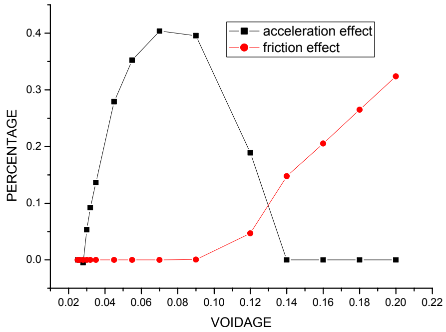


Figure 7 Acceleration and friction effect percentage when consider acceleration and friction

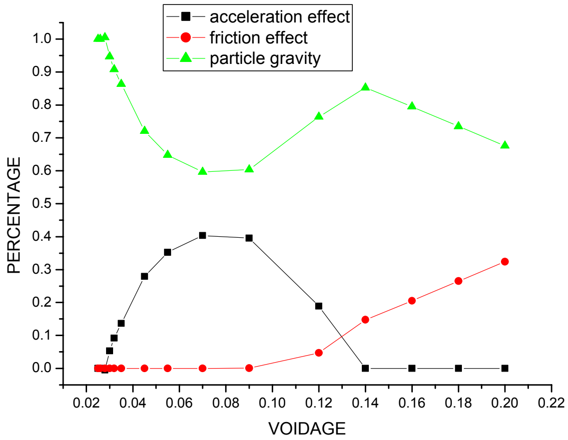


Figure 8 All the components of total pressure drop

The intrinsic relationships among the three components constituting the total pressure of the system can be summarized in figure 8. it can be observed that at the beginning of the riser, i.e. the relatively solid dense zone, the dominant factors leading to total pressure drop are hydrostatic head of solids(δ), solids friction and collision(β), and the proporation of the hydrostatic head of solids is approximately 70%. With the increase of the height along z direction, the solid become more dilute, and the influence of solid friction and collision keeping decreasing, moreover, at this time, the solid acceleration influence almost can be ignored. When the solid voidage falls to about 0.14, the component of hydrostatic head of solids(δ) reach its first peak value which is approxmiately 87%, the solid acceleration component (χ) became observational and keeping increasing with solid voidage decreasing. It is demonstrated by the figure 8 that when the solid voidage is in the range of 0.14 and 0.09, all the three components act on the total pressure drop simultaneously, however the component of hydrostatic head of solids(δ) is always dominant, and it's value change from 87% to about 60% when solid voidage change from 0.14 to 0.09. After solid voidage less than 0.09, the solids friction and collision(β) become not so important and can be ignored later. Both of the component of hydrostatic head of solids(δ) and solid acceleration component (χ) reach their peak values, whose values are 60% and 40% respectively. Since this point, the hydrostatic head of solids(δ) plays more and more important roles and solid acceleration component (χ) decreases little by little. Eventually, when solid voidage reach about 0.025, which is relatively dilute zone, solid acceleration component (χ) almost can be ignored again. And all the pressure drop are the result of solid hydrostatic head, that is to say, solid hydrostatic head is the only factor which result in the pressure drop along the CFB riser.

3. conclusion

In order to describible the hydrodynamic of the acceleration zone in the CFB riser, a new model based on the momentum banlance equation is built, which posses the ability to give comprehensive prediction to the flow struction and explain some intrinsic relationship among different factors leading to the total pressure drop along the riser. All at all, the calculation results show clearly that the other two components leading to the total pressure drop are far more than neglected.

From the mode prediction, it is demonstrated that at the dense zone of the riser, the pressure drop along the axial direction are mainly owe to the solid hydrostatic head (δ) and solids friction and collision(β)are the dominant facotrs. When solid voidage is in the certain range, all the three factors paly an important role in the hydrodynamic characteristic of the system. After that when solid is in relatively dilute zone, what the influencing factors are solid hydrostatic head (δ) and solid acceleration component (χ). Only when solid voidage reach certain dilute status, all other two factors can be neglected reasonably. Besides, regarding with what the quantitive percentage of each component in the total pressure drop relatively to how much the solid voidage, it closely depend on the actual system parameters and should be calculated on the individual basis.