HYDRODYNAMIC MODELING OF GAS-SOLIDS RISER FLOWS

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Abstract

Hydrodynamics plays a crucial role in optimum design and performance of circulating fluidized beds (CFB). The traditional approach of equating the static pressure drop to the bulk weight in a riser section overlook the effects of solids acceleration and kinetic energy dissipation due to solids collisions and inter facial frictions, which leads to an overestimation of local solids holdup. The overestimation of solids holdup is very significant in the acceleration and dense phase transport regions. This paper presents a mechanistic model based on gas-solid continuity and momentum equations, along with the modified drag force correlation and new formulation for moment dissipation of solids due to solids collisions. The proposed model yields the coupled hydrodynamic parameters of solid volume fraction, gas and solid velocity, and pressure distribution along the whole riser. The model predictions are reasonably validated against the published experimental data from four independent research groups for a wide range of operation conditions.

Keywords: Gas-solids Flow, Fluidization, Solid Acceleration, Energy Dissipation

1. Introduction

Gas-solids transports have found widespread applications in a varity of industrial processes such as fluid catalytic cracking (FCC), pulverized solid fuel combustion, coal gasification, and pneumatic conveying. The understanding of behaviors of such flow systems can significantly optimize the design and operation, and, in turn, the productivity. The traditional approach of equating the static pressure drop to the bulk weight in riser section overlook the effects of solids acceleration, kinetic energy dissipation due to interfacial friction between interstitial gas and suspended solids, solid-solid collisions and solid wall friction, which leads to overestimation of local solids holdup [2]. The overestimation of solids holdup is very significant in the acceleration and dense phase transport regions. The following gives a brief review of related modeling efforts and remaining challenges, which provides the background and modeling objective of this paper.

The actual flow structure of gas-solid flow in a riser is very complex with transient, multidimensional variations in axial, radial and azimuthal directions, multi-scaled phase interaction, and other complications from solid cohesions to electrostatic charges [2, 11]. Due to the neglect of solid acceleration and phase friction, the converted volumetric solid holdup is conceptually different from actual solid holdup, which in the bottom zone is much larger than the true average solid concentration [6]. In most of riser flow models, the solid motion is typically modeled based on the effective drag forces from semi-empirical correlations of gas-solid fluidization, such as the Richardson-Zaki equation. However, the Richardson-Zaki equation may not be adequate to describe the hydrodynamic forces on accelerating particles

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with a net transport mass flux in the riser because the solid holdup is expected to be a function of hydrodynamic characteristics of both gas and solids velocities rather than the gas velocity alone [9 , 2]. In fluidization most inter-particle collisions are off-center or oblique, in which the energy dissipation not only depends on the loss of normal component collision but also depends on the loss due to sliding and micro-slip friction in tangential and rolling contacts [4]. Hence the assumptions of friction free and center-to-center particle collision in vacuum in kinetic theory modeling approach may lead to appreciable biased predictions in particle flow hydrodynamics, especially in energy or pressure distributions.

In summary, the inter-particle collisions and particle-fluid interfacial forces have a significant impact on axial gradient of pressure in a riser flow. In the acceleration and dense phase transport regions, the effect of solid acceleration and kinetic energy dissipation may significantly alter the pressure distribution, which in turn distorts the distributions of solid concentration and phase velocities. The physical modeling of hydrodynamics of gas-solid flow through the riser is still quiet incomplete, and no modeling results are validated against experimental data of axial gradient of pressure, solids volume fraction, gas velocity, and solid velocity at the same time altogether under the same operating conditions . The objective of this paper is to presents a mechanistic hydrodynamics model of gas-solids flow through riser to predict the coupled hydrodynamics, i.e. the axial gradient of pressure and solid volume concentration along the riser. The highlights of our model include (1) some modifications of drag force due to the neighboring particle compaction and collisions and (2) a new momentum transfer of solids due to inter-particle collisions and its constraint on acceleration of solids. As a preliminary model, our current approach is still based on cross-sectional averages. It should be pointed out that such a modeling approach takes the advantage of greatly simplified mathematical formulation at the expense of losing radial non-uniformity or wall effect. To validate our model, predicted results are directly compared against the published experimental data from four independent research groups.

2 Theoretical Model & Closure

The actual gas and solids flow in a riser is a multi-dimensional, especially at the bottom of the riser where gas and solids are injected. However, for the concern of phase transport along the riser, a most common modeling approach is to assume that the phase properties vary as function of axial coordinate only, namely, one-dimensional flow. Each phase forms a continuum and the flow is considered to be steady [1].

Consider a gas-solids riser flow as shown in Figure 1. The flow is assumed to be steady and isothermal without any chemical reactions and the solids are spherical, non-porous, and mono dispersed with a uniform material density.

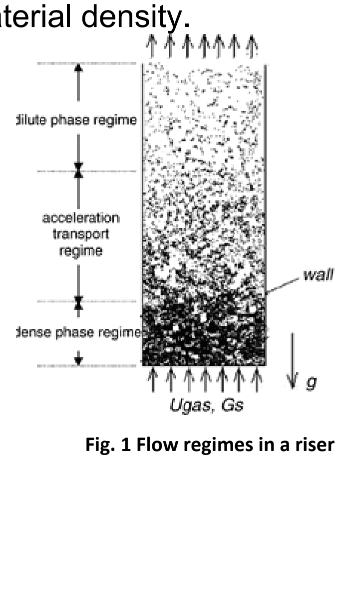

Fig. 1 Flow regimes in a riser

The riser flow is characterized by a dense region at the bottom of the riser, a dilute region at the top of riser and acceleration region in between. In the dense phase region, the solids concentration is very high, and the relative motion between the particles is very small. The particle-particle interaction can be very strong compare to particle-fluid interaction in dense phase region. In the acceleration region, the solids particles are accelerated asymptotically towards a state with constant velocity. In the dilute phase region, both the gas and solid lows are fully developed, and the particles are nearly uniformly distributed in the axial direction. In this region, the flow characteristics are invariant with the riser height. Here, we ignore the exit effect at the end of the riser.

2.1 Modeling with Uniform Radial Profiles

Due to the lack of knowledge of radial distributions of the flow parameters and the mechanisms governing the radial mass and momentum transports of both the gas and solids phases, the approximation with uniform radial profiles would be the simplest and most convenient to closure the problem. In addition the wall friction may be neglected. [10]

The summary of the independent governing equations used for describing the model to find the axial gradient of pressure, axial profile of solid volume fraction and phase velocities are summarized below.

Gas and solids continuity equation

$$\overline{\alpha}_g \rho_g U_g = G_{g0} \qquad (1)$$

$$\overline{\alpha}_s \rho_s U_s = G_{s0} \qquad (2)$$

Gas and solids Momentum balance

$$-\frac{dP}{dz} = \overline{\alpha}_g \rho_g g + \overline{\alpha}_g \rho_g u_g \frac{du_g}{dz} + F_D \qquad (3)$$

which shows that, the pressure gradient is balanced against gas weight, gas acceleration and drag force.

$$F_D = \overline{\alpha}_s \rho_s g + G_s \frac{dU_s}{dZ} + \gamma \qquad (4)$$

which shows that, the particle-fluid interfacial force balances for the solids weight, solids acceleration, and a compact momentum from solids collisions that constrain the solids acceleration.

To solve the above equations, we must know intrinsic correlations for γ and F_D.

2.2 Constitutive Equations

In a dense-phase fluidized bed where the statistical average solid velocity is null. Wake effects are very much damped in this flow region. The particle-fluid interfacial force is typically expressed by Richard-Zaki equation, which is constituted purely based on the modifications of the drag force on a single particle in the flow.

$$F_{D0} = \frac{18\mu}{d_s^2} \cdot \frac{\overline{\alpha}_s}{(1-\overline{\alpha}_s)^n} \cdot (U_g - U_s) \tag{5}$$

n - Richard-Zaki index(with an experimental value around 4 ~ 5).

In the solids acceleration regime, the stabilized wake effect become too important, this leads to reduction in drag force of trailing particles of collision pair [12, 13]. Hence, the modified drag force may be expressed by:

$$F_D = k_1 F_{D0} \tag{6}$$

K_1 is the coefficient of wake effect of the neighboring particles on the particle-fluid interfacial force [12], which is represented as,

$$k_1 = 1-(1-A)\exp\left[B \cdot \left(\sqrt[3]{\frac{\pi}{6\overline{\alpha}_s}} - 1\right)\right] \tag{7}$$

In dense phase riser flow region, particles collide with each other and the loss of kinetic energy due to inter-particle collision can-not be neglected. The main factors which govern the axial compact momentum of solids phase include:

i) Disturbance of local solids acceleration, which can be expressed by slip velocity ($u_g - u_s$).
ii) Effect of compacting and colliding frequency between solid particles, which is presented by the local solids concentration (α_s).
iii) Physical properties of the particle and fluid, which is expressed as the particle terminal velocity (u_{pt})

Based on the above information, a simple model for axial compact momentum of solids phase (γ) is proposed as:

$$\gamma = \frac{\rho_s g}{u_{pt}}(1-k_2 k_3)\frac{k_1 \overline{\alpha}_s}{(1-\overline{\alpha}_s)^4}(u_g - u_s) \tag{8}$$

where, k_2 & k_3 represent respectively, the cascading effect of particles distribution structure and acceleration factor which are dominated by the solids volume fraction, as give below:

$$K_2 = \left[1-\exp\left(-\left(\frac{\bar{\alpha}_s + 0.2}{\alpha_{sc}}\right)^2\right)\right] \tag{9}$$

$$K_3 = \frac{1}{\pi}\tan^{-1}\left[\frac{24-100\cdot\overline{\alpha}_s}{0.9}\right]+0.5 \quad (10)$$

It is noted that K_2 represents a s-shaped axial profile for cross-sectional averaged voidage in riser [Li & Kwauk, 1980].

With the sub models of the intrinsic mechanisms of the particle-fluid interfacial force and collisional momentum term, the coupled equations 1 to 4 now can be solved to find four coupled variables namely pressure (P), solids volume fraction (α_s), gas velocity (U_g) and solids velocity (U_S), which are the essential parameters to understand a gas-solids two phase riser flow. The input boundary conditions to simulate our model results are corresponding to the experimental conditions.

3. Results & Discussion

In order to validate the proposed model, the model predictions of solid volume fraction and axial distribution of pressure are directly compared with the experimental data of different independent research groups [8, 5, 7, and 6]. The operating conditions of the experiments used for the comparison of the proposed model predictions are shown in Table 1.

Table 1 Experimental parameters for model validation.

Case/ [Ref. No.]	Particle Type	d_p (μm)	G_s (kg/m^2.s)	U_g (m/s)	ρ_s (kg/m^3)	Z (m)	D (m)
1[8]	Glass Beads	88	600	7	2600	6.4	0.041
2[8]	Glass Beads	88	382	7	2600	6.4	0.041
3[8]	Glass Beads	88	199	7	2600	6.4	0.041
4[5]	FCC	76	489	5.2	1712	14.0	0.041
5[5]	FCC	76	489	7.6	1712	14.0	0.041
6[5]	FCC	76	489	11	1712	14.0	0.041
7[5]	Sand	120	50	4.2	2600	14.0	0.041
8[7]	Sand	208	400	8.5	2580	5.0	0.05
9[7]	Sand	208	240	8.5	2580	5.0	0.05
10[7]	Sand	208	700	8.5	2580	5.0	0.05
11[6]	Quartz Sand	105	23	4	2600	15.6	0.04

Figure 2 shows that, the model predictions for solid volume fraction fit the experimental data [8] satisfactorily along the riser height. Basically the distribution of solid volume fraction along riser height presents typical S-shape. It means that in the lower part of the riser, the flow is in the dense phase regime because of the low initial solids velocity. Then the solids are gradually accelerated under the interaction with gas phase, and finally reach the relatively steady and dilute regime at the upper part of riser. Fig.-2 also shows that, in the dilute phase transport regime, solid volume fraction remains constant in the rest of the riser height for all three cases. The proposed model predictions demonstrate the same trend as experimental measurement and quantitatively match with their values along the whole riser with reasonable accuracy.

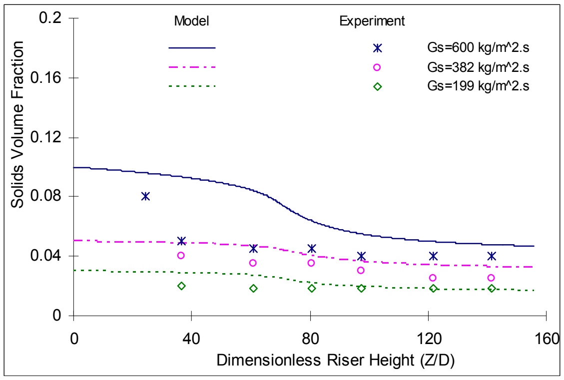

Figure 2 Comparison of model predictions and experimental results of axial profile of solid volume fraction in CFB riser of 0.041 m ID and 6.4 m high, at U_o=7 m/s and d_p= 88 μm[8]

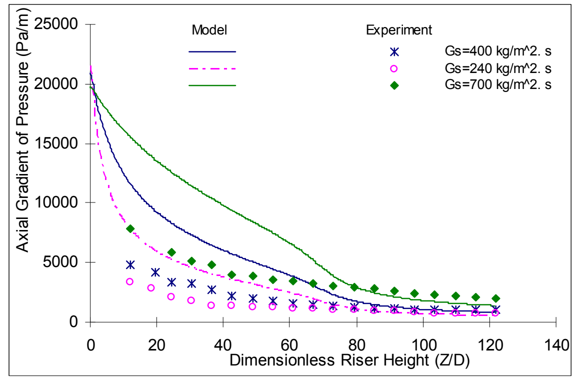

Figure 3 Comparison of model predictions and experimental results of axial pressure gradient profile in CFB riser of 0.05m ID and 5.0 m high, at U_o=8.5 m/s and d_p= 208 μm [7]

For the validation of model predictions of the axial pressure drop, the following fig. 3, 4 and 5 gives the detail comparison between model prediction and experimental measurement [7, 5].

Fig. 3 shows a reasonable agreement between model prediction and experimental data for axial gradient of pressure, although results are over predicted in bottom zone of riser. As demonstrated in figure 3, in the lower part of the riser, the axial gradients of pressure are much steeper than in the upper part. This phenomenon is due to fact that, in the lower part of the riser the gas-solid flow is in the dense phase regime, where violent inter-particle collision, normal compression, rebounding, sliding and non-sliding micro-slip rolling are the dominant factors for overall energy dissipation, which is much higher than in the upper part of the riser, where the energy dissipation is mainly by friction loss and gravity. The solid phase is accelerated gradually with the increase of riser height and the dense gas-solid flow enters in to the acceleration transition regime and then dilute transport regime. The inter-particle spacing becomes larger and larger in dilute phase transport regime and hence, the energy dissipation is dominated only by friction loss between gas/solid and wall, which turned out to be relatively small, leading to a quite steady axial pressure gradient in the upper part of the riser.

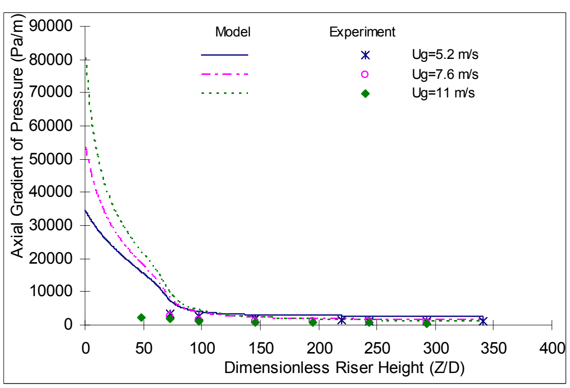

Figure 4 Comparison of model predictions and experimental results of axial pressure gradient profile for FCC particles in CFB riser of 0.041 m ID and 14.0 m high, at G_s= 489 kg/m^2 s and d_p= 76 μm [5]

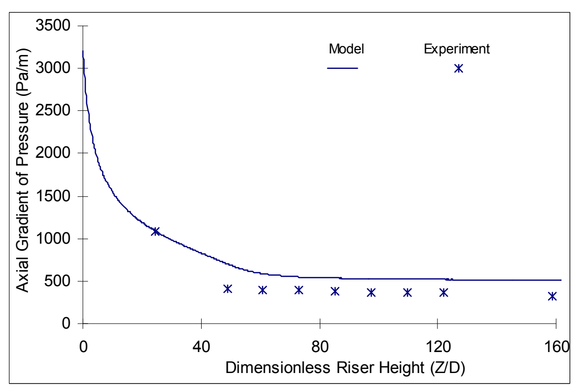

Figure 5 Comparison of model predictions and experimental results of axial pressure gradient profile for sand particles in CFB riser of 0.041 m ID and 14.0 m high, at U_o = 4.2 m/s, solid flux G_s= 50 kg/m^2 s and d_p= 120 μm [5]

Figure 4 shows the model predictions for the axial gradient of pressure for the experimental data [5] for sand particles. The pressure drop gradient along the whole riser demonstrate similar tendency as shown in Figure 3. It is seen that, the proposed model fits the experimental data satisfactorily with the exception at transition between the dense and dilute regions. This discrepancy may be caused by the fact that in this region, the dominant effect of pressure drop are due to the combined effect of inter-particle collision and solid acceleration, hence the pressure drop changes are very intensive within a very short distance which may lead to a relatively large measure error.

Figure 5 shows that, the results of model predictions are in close parity of experimental data [5], which suggests a fair good agreement between the proposed model predictions and experimental data. The above discussion shows that, the proposed model predictions on solid volume fraction and axial pressure gradient have been validated against different sets of experimental data, which show fair a agreement.

4. Conclusion

A simple mechanistic model is developed, which describes the mechanism to account for the effect of neighboring particle compaction and collision on drag force by modifying the traditional Richard-Zaki equation for the drag force on a single particle in the flow. An intrinsic correlation for momentum transfer of solids phase is derived to account for the inter-particles collisions. This mechanistic model not only gives the prediction of solid volume fraction, gas and solid velocity, but also is capable of predicting the axial pressure distribution along the whole riser at the same time.

The model predictions are compared with the axial gradient of pressure and solid volume fraction for the experimental data of four different independent research groups. The model predictions show fairly good agreement with the experimental data in the bulk range. Moreover, systematic parametric studies have been conducted to demonstrate the effects of variation in gas velocity and solid mass flux on flow patterns.

Nomenclatures

A	Cross sectional area of riser	D	Riser diameter
d_s	Particle diameter	F_D	Corrected drag force
F_{Do}	Drag force (Richardson-Zaki)	g	Acceleration of gravity
G_g	Gas mass flux	G_s	Solid mass flux
G_{so}	Cross-sectional averaged mass flux of solids phase at inlet	l_w	Circumferential length of riser
		P	Pressure
P_{atm}	Gas pressure at inlet	u_g	Local gas velocity
U_g	Cross-sectional averaged velocity of gas	U_o	Superficial gas velocity
		U_{pt}	Particle terminal velocity
U_s	Cross-sectional averaged velocity of solids	u_s	Local particle velocity
Z	Axial position in riser	α_g	Gas volume fraction
α_s	Solid volume fraction	$\overline{\alpha}_s$	Cross-sectional average volume fraction of solids
$\overline{\alpha}_g$	Cross-sectional average volume fraction of gas	α_{sc}	Solid volume fraction inflection point for faster fluidization
γ	Solid momentum dissipation due to	ρ_o	Density of gas at inlet

inter particle collision

τ_w Wall shear stress of gas phase

ρ_g Gas density

τ_{sw} Wall shear stress of particle

μ Kinematic viscosity of gas phase

ρ_s Particle density

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