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MODELING ON HETEROGENEOUS STRUCTURE IN ACCELERATION REGIME OF GAS-SOLID RISER FLOWS

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ABSTRACT

Recent measurement of solid concentration in gas-solid riser flows by Electric Capacitance Tomography (ECT) reveals a strong heterogeneous structure, typically represented by a core-annulus-wall zone pattern. In this paper we present a mechanistic model in which the formation of the heterogeneous structure is due to the radial migration of solid flow from the wall toward center as well as due to the non-uniform acceleration of solids across the cross-section near the bottom of the riser. Firstly we present the general governing equations and discuss problem closure; then a simplified model with one-way flow coupling between the wall region and the core-annulus region is proposed to simulate the formation and development process of heterogeneous flow structures in the riser. Typical results of the three-zone flow structure along the riser are illustrated, which include the axial distributions of solids concentration and phase velocities in each zone, in addition to the pressure distributions. The model is also validated against the ECT measurements.

INTRODUCTION

Recent measurement using Electrical Capacitance Tomography (ECT) reveals a radial symmetry of the time-averaged solids holdup distribution, and shows that there exists a double ring structure in solids concentration in a circulating fluidized bed riser [Du et al., 2004 (1)]. As shown in Figure 1, the solids concentration in the core near the riser bottom is much denser than that in the annulus (as much as five times)

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering, Art. 13 [2007]

whereas the solids concentration in the core is less than that in the annulus near the riser top. Across any cross-sections, the solids in the wall regions always have the highest concentration. This core-annulus-wall structure appears to be stable along the riser, and holds for a wide range of CFB operation conditions. Such findings are very interesting because these indicate that the radial profile for some dense circulating fluidized beds could be of a core-annulus-wall three-region structure, instead of the core-annulus (wall) structure or two-region structure.

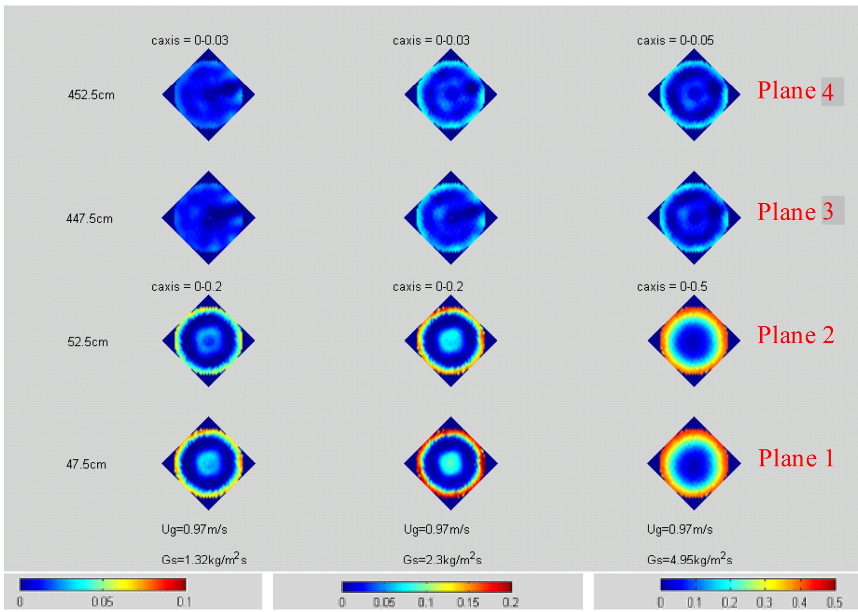


Figure 1 Wall-Annulus-Core Structure in CFB [Du *et al*., 2004]

Most models on heterogeneous flow structure are based on the core-annulus (wall) flows [Bolton and Davidson, 1988 (2); Rhodes and Geldart, 1987 (3); Horio et al, 1988 (4); Senior and Brereton, 1992 (5)], which typically consider a dilute uniform core flow, and a dense wall flow along the riser. Most of these models ignore the detailed mechanisms in the bottom region of riser where the flows can be very dense and complex. A primitive model was lately proposed to interpret the reported core-annulus-wall structure [Zhu et al., 2005 (6)], using a simplified kinetic theory model to account for the solids acceleration in collision dominated dense flow regimes near the bottom of riser. It is realized, however, that most traditional momentum-based models with the assistance of kinetic theory modeling approach may be insufficient to describe some basic physics of collision-induced energy dissipation in fluidization, such as energy dissipations from tangential slip and rotational slip. This deficiency may be represented by the inability of correctly predicting the pressure distribution in the dense flow regime near the bottom of a CFB riser. The importance of correct account of energy transport and dissipation in the momentum equation may be analogous to that of k-ε model in the turbulent momentum transport equations in turbulence flows. Hence an additional term due to energy dissipation should be introduced in solid momentum transport equation in the collision and acceleration dominated regime [Zhu and You, 2006 (7)].

This paper is aimed to present a complete mechanistic modeling approach to characterize the formation mechanisms of heterogeneous structure in a CFB riser.

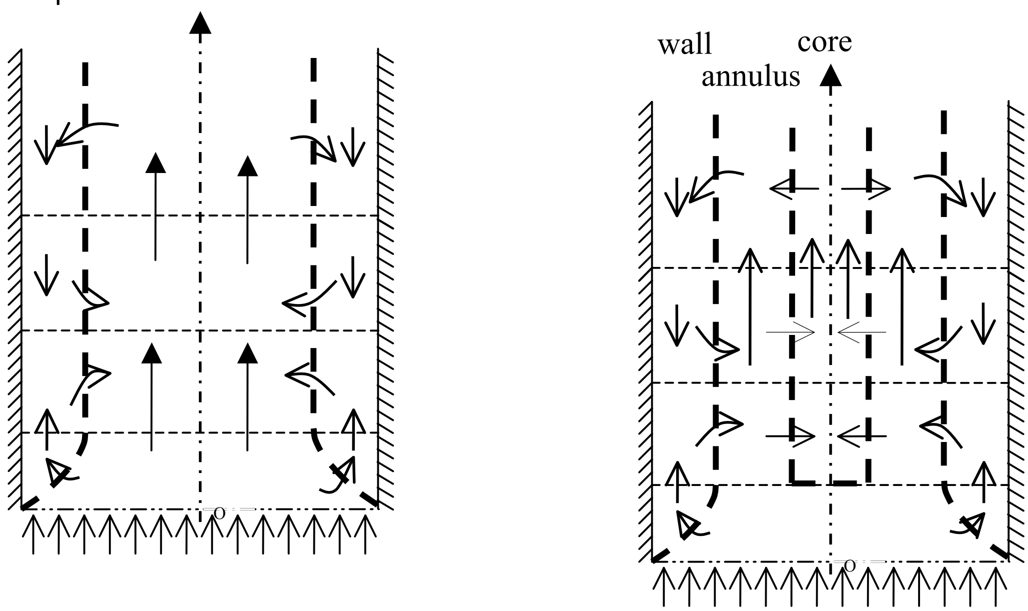
FORMATION MECHANISMS OF HETEREOUS FLOW STRUCTURE

Consider a CFB riser in Figure 2, where a uniform gas-solids flow is at the riser inlet and a dilute flow is in the core-annulus region with down solids near the wall at the riser outlet. A wall (boundary layer) region of dense solids concentration is developed from riser bottom because the averaged gas velocity in the wall region becomes too low to support upward moving solids. At a certain bed height, the solids in the wall region have exhausted all their initial upward momentum and begin to move downward. At this location the averaged solids velocity in the wall region is null. Hence, in the bed section near this height, all solids from the upper wall region or from the lower wall region are forced to migrate inwardly towards the riser column center [Rhodes et al., 1998 (8)]. In a high convection riser flow (i.e., at a high fluidization velocity and low solids loading) with little or moderate back mixing, the inwardly migrating solids are all entrained into the flow without any residual solids reaching to the center of the riser. In this case, the flow pattern is commonly known as “core-annulus” two-region flow, where the radial solids concentration gradually decreases towards the centerline of riser, as illustrated in Figure 2(a). In other cases, especially with low fluidization velocities, part of the inwardly migrating solids may reach to the centerline region of riser. Due to axial symmetry of the riser, a dense core region must be resulted, as shown in Figure 2(b). Required by a nearly-equal axial pressure gradient in all regions at the same bed height, the gas velocity in the core tends to be lower than that in the annulus where the solids concentration is less. This lowered gas velocity in the core leads to a slower solids acceleration in the core, and hence preserve this core-annulus-wall structure with a higher solids concentration at the core along the riser. In the mean time, based on the mass balance of solids, the downward moving solids in the wall region in the upper part of a riser must come from those solids in the annulus and core. Hence, in the upper part of the riser, the solids migration into the wall yields depletion in solids concentration, which is more severe in the core than in the annulus. Therefore, near the top of a riser, a core-annulus-wall structure still exists but with less solids in the core than in the annulus. The formation mechanism of the core-annulus-wall flow structure, with a qualitative agreement to those ECT findings in Figure 1, is hence fully explained. Following, we would discuss the mathematical modeling of the core-annulus-wall structure in a riser flow.

GENERAL GOVERNING EQUATIONS AND PROBLEM CLOSURE

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering, Art. 13 [2007]

In order to describe the core-annulus-wall flow structure, independent governing equations must be established for gas velocities, solid velocities and solid volume fractions in all regions, region cross-sectional areas, solids flows across regional interface, and the pressure along the riser height. The following is a summary of these equations.



(a) Core-annulus (wall) model (b) Core-annulus-wall model

Figure 2 Heterogeneous flow structures in CFB.

Geometric relations and Equation of State:

$$A = A_c + A_a + A_w \tag{1}$$

$$\rho = \frac{p}{RT} \tag{2}$$

$$\alpha_i + \alpha_{si} = 1,\ \ i = a, c, w \tag{3}$$

Mass Balance of Solids

Overall balance: $$G_s A = \rho_s \alpha_{sc} U_{sc} A_c + \rho_s \alpha_{sa} U_{sa} A_a + \rho_s \alpha_{sw} U_{sw} A_w \tag{4}$$

Core-region: $$\frac{d}{dz}(\alpha_{sc}\rho_s U_{sc} A_c) = \dot{m}_{sc} \tag{5}$$

Annulus region: $$\frac{d}{dz}(\alpha_{sa}\rho_s U_{sa} A_a) = \dot{m}_{sw} - \dot{m}_{sc} \tag{6}$$

Wall region: $$\frac{d}{dz}(\alpha_{sw}\rho_s U_{sw} A_w) = -\dot{m}_{sw} \tag{7}$$

Mass Balance of Gas $$GA = \rho\alpha_c U_c A_c + \rho\alpha_a U_a A_a + \rho\alpha_w U_w A_w \tag{8}$$

Gas Momentum Balance

Overall $$\frac{d}{dz}(\sum_{i=a,c,w}\alpha_i\rho U_i^2 A_i) = -\frac{dp}{dz}A - \sum_{i=a,c,w}F_{Di}A_i - \sum_{i=a,c,w}\alpha_i\rho g A_i - F_{fww} \quad (9)$$

Core-region: $$\frac{d}{dz}(\alpha_c\rho U_c^2 A_c) = -\frac{dp}{dz}A_c - F_{DC}A_c - \alpha_c\rho g A_c - F_{fac} \quad (10)$$

Annulus-region $$\frac{d}{dz}(\alpha_A\rho U_A^2 A_A) = -\frac{dp}{dz}A_A - F_{DA}A_A - \alpha_A\rho g A_A + F_{fac} - F_{faw} \quad (11)$$

Wall region: $$\frac{d}{dz}(\alpha_w\rho U_w^2 A_w) = -\frac{dp}{dz}A_w - F_{DW}A_W - \alpha_w\rho g A_w - F_{fww} + F_{faw} \quad (12)$$

where F_{faw}, F_{fac}, F_{fww} are interfacial frictional forces or momentum transfer at regional or wall boundaries. F_{DA}, F_{DC}, F_{DW} are drag forces in each region.

Momentum Balance of Solids

$$\frac{d}{dz}(\sum_{i=a,c,w}\alpha_{si}\rho_s U_{si}^2 A_i) = \sum_{i=a,c,w}F_{Di}A_i - \sum_{i=a,c,w}\alpha_{si}\rho_s g A_i + \sum_{i=a,c,w}\frac{d}{dz}(C_{ppi}\frac{dU_{si}}{dz}) - F_{fsw} \quad (13)$$

Core-region: $$\frac{d}{dz}(\alpha_{sc}\rho_s U_{sc}{}^2 A_c) = F_{DC}A_c - \alpha_{sc}A_c\rho_s g + \frac{d}{dz}(C_{ppc}\frac{dU_{sc}}{dz}) + \dot{m}_{sc}U_{sc} \quad (14)$$

Annulus-region: $$\frac{d}{dz}(\alpha_{sa}\rho_s U_{sa}{}^2 A_a) = F_{DA}A_a - \alpha_{sa}A_a\rho_s g + \frac{d}{dz}(C_{ppa}\frac{dU_{sa}}{dz}) - \dot{m}_{sc}U_{sa} + \dot{m}_{sw}U_{sw} \quad (15)$$

Wall-region: $$\frac{d}{dz}(\alpha_{sw}\rho_s U_{sw}{}^2 A_w) = F_{DW}A_w - \alpha_{sw}A_w\rho_s g + \frac{d}{dz}(C_{ppw}\frac{dU_{sw}}{dz}) - \dot{m}_{sw}U_{sw} - F_{fsw} \quad (16)$$

where C_{ppc}, C_{ppa}, C_{ppw} are transport coefficients due to inter-particle collision in each region.

Definition of Regional Boundaries

Based on ECT measurements [Du et al., 2004 (1)], we may assume that

$$\frac{dA_w}{dZ} \approx 0 \quad (17)$$

$$\frac{A_c}{A_a} = Const \quad (18)$$

Thus, we have 14 independent equations ((1) - (3), (6) - (8), (10) - (18)) for 14 independent variables (A_c, A_w, A_a, U_{sc}, U_{sa}, U_{sw}, α_{sc}, α_{sa}, α_{sw}, U_c, U_a, U_w, P, ρ).

SIMPLIFIED MODEL

To simplify the problem solution, we adopt the one-way flow coupling between the wall region and the core-annulus region. Namely, the gas-solid flows in the wall region are predetermined from wall boundary conditions and de-coupled from the governing equations of the core and annulus region. Hence the problem is simplified as a core-annulus flow with a given axial distribution of solids migration from the wall region along the riser. We further ignore all the interfacial frictional forces across the regional boundaries.

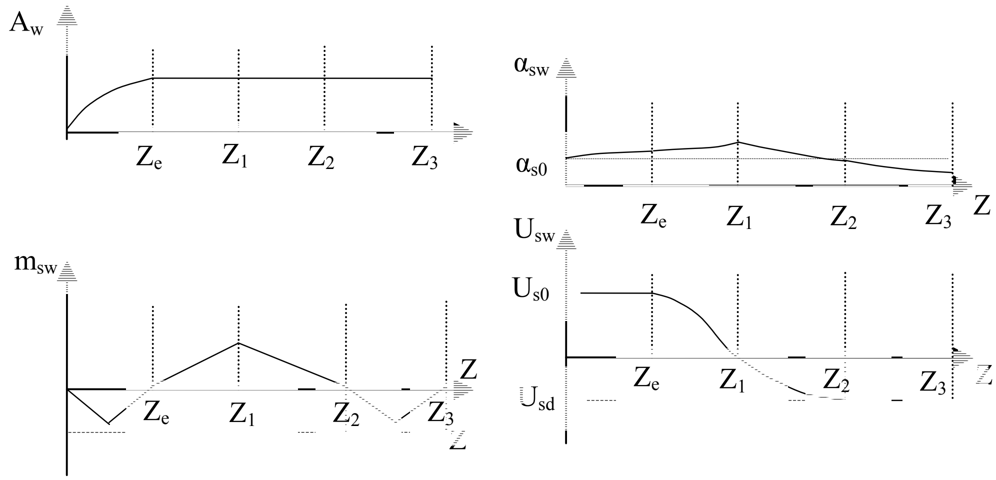


Figure 3 Schematic profiles of solid flow in the wall region

Flows in Wall Region

Schematic flow distributions in the wall region are demonstrated in Figure 3, where Ze, Z1, Z2 and Z3 denote the characteristic heights of entrance regime, up-moving solids in wall, outward-migrating solids in the down-moving solids wall region, and the total height of riser.

Intrinsic Correlations and Equations

Based on Richard -Zaki equation [Richardson and Zaki, 1954 (9)], we may have,

$$F_{Di} = \frac{18\mu}{d_{si}^2} \cdot \frac{\alpha_{si}}{(1-\alpha_{si})^L} \cdot (U_i - U_{si}) \tag{19}$$

The addition solid momentum transport due to energy dissipation in the dense and acceleration region can be expressed by,

$$\frac{d}{dz}(C_{ppi}\frac{dU_{si}}{dz}) = -\frac{A_i}{U_{si}}\left(\Gamma_i - (U_i - U_{si})(-\frac{dP}{dz})\right) \tag{20}$$

where Γ_i represents the energy dissipations due to inter-phase frictional and inter-particle collision. Γ_i can be approximated by [Zhu and You, 2006 (7)]

$$\Gamma_i \approx \sum_{j=0}^{N} k_j \alpha_{si}^j \tag{21}$$

the coefficients k_j depend on solids flow characteristics at minimum transport.

After above simplifications, we obtain 7 independent equations for 7 independent variables in the annulus and core regions, namely, U_{sc}, U_{sa}, α_{sc}, α_{sa}, U_c, U_a, P.

RESULTS AND DISCUSSION

To validate our model, the model predictions have been compared against the ECT measurements, as shown in Figure 4. Details of the ECT measurement system are given in Du et al. (2004). The experiment was performed in a riser of 50 mm diameter, with FCC catalysts. The solids circulation rate is 1.32 kg/m2-s and the gas velocity is 0.97 m/s. Both measurements and model predictions show that, along the riser, the solid concentrations in the core and annulus regions decrease much faster than that in the wall region. Our model suggests that there exists a peak in solids concentration in the wall region, possibly due to the impact between downward solids from back mixing and upward solids from entrance. Figure 4 demonstrates a fairly good agreement between measurements and model predictions.

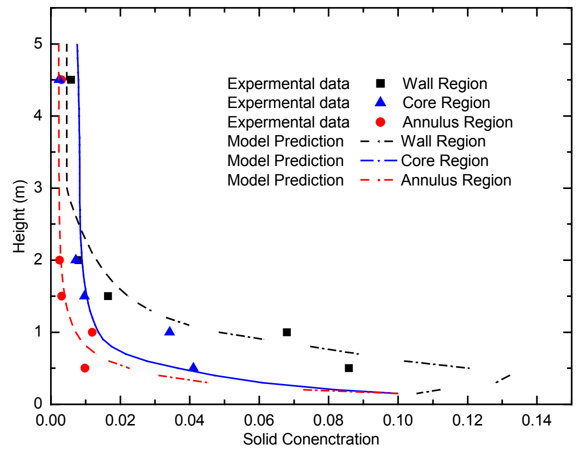


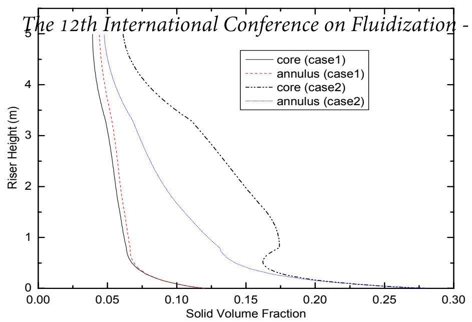
Figure 4 Solid Concentration vs Height

The existence of core-annulus-wall structure depends on the flow conditions. In the following, we present two simulation examples, one showing the core-annulus (wall) flow structure and the other showing the core-annulus-wall structure. The flow conditions, solids properties, and riser geometric parameters are listed in Table 1.

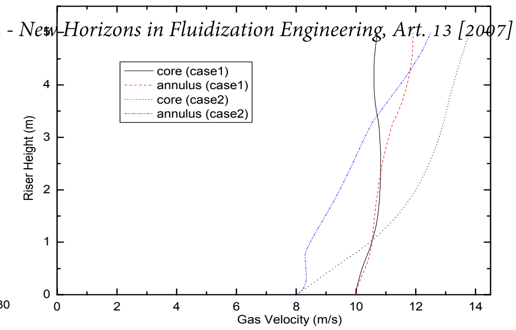
Figure 5 shows the typical axial distributions of gas and solids in the core and annulus regions. The axial distributions of solid volume fraction are shown in Figure 5(a). For case-1, there is no substantial difference between the core and the annulus region (with a leaner concentration in the core), whereas for case-2, due to strong

Table 1 Parameters of simulation examples

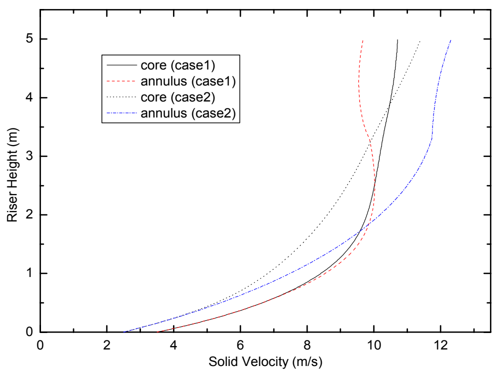
Case	Gas		Particle				Riser	
	α	Velocity m/s	ρ_s kg/m^3	G_s kg/m^2-s	χ	d_s μm	Z m	Diameter m
1	0.9	10	1500	200	0.15	70	5	0.20
2	0.7	8	1500	650	2	70	5	0.20



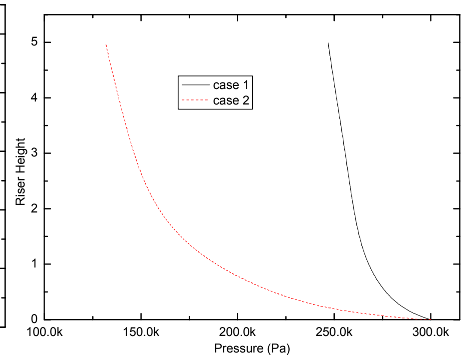
(a) Solid volume fraction vs. Height



(b) gas velocity vs. Height



(c) Solid velocity vs. Height



(d) Pressure vs. Height

Figure 5 Typical axial distributions of gas-solid flows in riser.

migration of solids from wall region, a dramatic increase of solids hold-up in the core region near the dense and acceleration regimes may occur, with a moderate decrease of solids hold-up in the annulus region. The corresponding axial distributions of solid velocities are given in Figure 5(c), which shows that the axial distance of solids acceleration is at a level of 1 -2 m. Hence case-1 may represent the commonly known “core-annulus” structure whereas case 2 may reveal the newly discovered core-annulus-wall structure. Figure 5(b) yields the axial distributions of gas velocities. The increase in averaged gas velocity is not only due to the possible gas entrainment from wall region but also due to the decreased absolute pressure along the riser. Figure 5(d) shows the axial distribution of pressure. For the convenience of comparison, we assume that the inlet pressure at the riser bottom is the same for both cases. As expected, the pressure drop in case-2 is much larger than that in case-1.

CONCLUSION

This paper presents a complete mechanistic model to interpret the heterogeneous flow structure in riser flows with uniform flow inlet conditions at the bottom of the riser.

The proposed mechanisms and corresponding mathematical modeling yield a reasonable explanation not only for the commonly known "core-annulus (wall)" flow structure but also the newly-reported "core-annulus-wall" flow structure in riser flows. Typical axial distributions of gas and solids phases along the riser are obtained from our modeling. More quantitative comparison with measurements and better modeling of involved intrinsic correlations (such as for back mixing ratio and inter-regional transfer) will be conducted in future studies.

LIST OF SYMBOLS

A	area
C_{ppi}	transport coefficient
d_s	average size of solid particles
F_{Di}	drag force
F_{fii}	friction force
G	flow flux
$\dot{m}_s$	solids transfer across interface
N	solid number in unit volume
p	pressure
U	velocity
z	bed height
α	solid concentration
μ	viscosity
ρ	density
Γ	energy dissipation function
χ	Back-mixing Ratio (Gback/Gs)

Subscripts

a	annulus region
c	core region
g	gas phase
s	solid phase
w	wall region

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