Flow of Dilute Gas-Particle Suspensions

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A semi-empirical model of the radial segregation of solids in upward flow of dilute gas-particle suspensions in riser systems is presented on the basis of a reduced form of the fundamental two-phase flow governing equations and experimental evidence concerning the solids concentration at the wall. The following simple expression for the radial solids concentration profile is obtained:

$$\frac{1-\epsilon}{1-\bar{\epsilon}}=2\left(\frac{r}{R}\right)^2$$

and is in agreement with experimental data over a wide range of operating conditions: superficial gas velocity from 1.4 to 15.3 m/s, riser diameter from 0.032 to 0.40 m, imposed solids flux from 6.60 to 207 kg/m^2·s, mean particle size from 32 to 120 μm and particle density from 1,000 to 3,500 kg/m^3.

The model confirms the existence of the core-annulus flow structure in gas-particle suspensions reported in riser reactors, circulating fluidized beds, and the freeboard of bubbling fluidized beds.

Introduction

The upward flow of dilute gas-particle suspensions in ducts is common to many industrial applications. Examples include the circulating fluidized-bed riser, the petrochemical riser reactor and the freeboard of the bubbling fluidized bed. The flow regime common to these examples, described by Geldart and Rhodes (1986) as refluxing dilute-phase transport, comprises a rapidly-rise core having a low concentration of solids, surrounded by a slowly-falling region near to the column wall, where the solids concentration is generally far greater. In ducts of circular cross section, this has become known as core-annulus flow.

Although many experimental observations of this regime have been presented (for example, Hartge et al., 1988; Herb et al., 1989; Gajdos and Bierl, 1978; Mineo, 1989), little theoretical explanation has been offered for these observations.

In this article, by simplification of the governing equations, a semi-empirical model is developed and expressions are derived for the radial variation in suspension concentration and radial particle velocity for the case of steady, isothermal, upward-flow of a gas-particle suspension in a circular pipe. Predictions are compared with available experimental data for gas-particle systems operating in the refluxing transport regime.

Theory

For an inert fluid-particle system, flowing in a steady, isothermal fashion in an upward direction in a circular pipe, the radial motion can be approximated by the following equations:

Continuity: with $\rho_f \ll \rho_s$ or considerably more solid than fluid movement in the radial direction

$$(1-\epsilon)\rho_s r u_s = C_1 = \text{constant} \tag{1}$$

Momentum: with du_f/dr, $d^2u_f/dr^2 \cong 0$ or little or no fluid acceleration in the radial direction

$$\mu_f \frac{u_f}{r^2} = F_{i,r} \tag{2}$$

$$(1-\epsilon)\rho_s u_s \frac{du_s}{dr} = -F_{i,r} \tag{3}$$

Here $F_{i,r}$ is the interphase force which may be obtained by extending Stokes' law as:

$$F_{i,r} = \frac{18}{d^2}(1-\epsilon)\mu_f(u_s-u_f) \tag{4}$$

thus ignoring the stress due to the solid phase at low concentration.

In the above equations u are velocities in the radial direction r, μ_f the fluid viscosity, $(1-\epsilon)$ the radial suspension concentration, ρ_s the density of the solids and subscripts f and s refer to the fluid and solid phases respectively. The above equations combine to produce:

$$0=\frac{C_1 du_s}{\mu_f dr}+\frac{r u_s}{r^2+M\mu_f}\cong\frac{C_1}{\mu_f}\frac{du_s}{dr}+\frac{u_s}{r} \tag{5}$$

where $M\mu_f=d^2/18\ (1-\epsilon)\ll r^2$ for very small particle sizes in the region of interest (that is, away from the axis of the pipe). A general solution of Eq. 5 takes the form:

$$u_s=C_2 r^{-\mu_f/C_1} \tag{6}$$

with C_2 is another constant, like C_1 is yet to be determined.

The radial suspension concentration profile may now be obtained by combining the above equation with Eq. 1, that is

$$1-\epsilon=\frac{1}{\rho_s}\frac{C_1}{C_2}r^{\left(\frac{\mu_f}{C_1}-1\right)} \tag{7}$$

We may now introduce a mean radial concentration, $(1-\bar{\epsilon})$

$$1-\bar{\epsilon}=\frac{1}{\pi R^2}\int_0^R 2\pi(1-\epsilon)dr \tag{8}$$

to eliminate the constant C_2 in Eq. 7 and obtain:

$$(1-\epsilon)/(1-\bar{\epsilon})=\frac{1}{2}\left[1+\frac{\mu_f}{C_1}\right]\left(\frac{r}{R}\right)^{\left(\frac{\mu_f}{C_1}-1\right)} \tag{9}$$

Alternatively, we may introduce $(1-\epsilon_w)$, the concentration at the pipe wall and obtain:

$$(1-\epsilon)/(1-\epsilon_w)=\left(\frac{r}{R}\right)^{\left[\frac{\mu_f}{C_1}-1\right]} \tag{10}$$

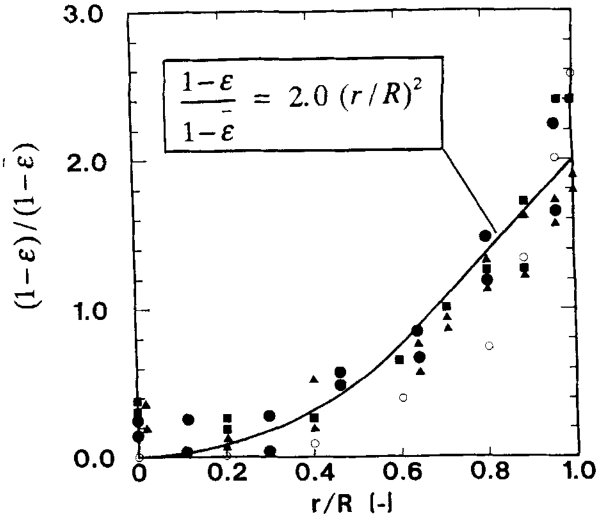
These two equations provide a useful basis for comparison with experimental data as they combine to produce:

$$(1-\epsilon_w)/(1-\bar{\epsilon})=\frac{1}{2}\left(1+\frac{\mu_f}{C_1}\right) \tag{11}$$

Examination of the data for systems involving air at ambient temperature and pressure (Herb et al., 1989; Mineo et al., 1989; Hartge et al., 1988; and Berker et al., 1986; see Figure 1) reveals that in the refluxing transport regime:

$$(1-\epsilon_w)/(1-\bar{\epsilon})=\frac{3}{2}\ \text{to}\ \frac{5}{2},\ \text{or a mean of 2} \tag{12}$$

which provides a semi-empirical means to establish the constant C_1/μ_f,



Authors	Key	Z (m)	2R(m)	U_o(m/s)	G_s(kg/m²s)
Herb et al. (1989)	●	1.6	0.150	3.8	26
		4.7			
Mineo et al. (1989)	■	1.35	0.205	4.0	34
Hartge et al. (1988)	▲	2.7	0.400	2.9	49
				3.7	30
Berker et al.(1986)	○	5.33	0.178	15.3	122.2

Figure 1. Comparison of theoretical results with experimental data in the refluxing dilute phase transport regimes from various sources all using air at ambient temperature and pressure.

$$\frac{C_1}{\mu_f}=\frac{1}{4}\ \text{to}\ \frac{1}{2},\ \text{or a mean of}\ \frac{1}{3} \tag{13}$$

The solution is closed and the prevailing equations become:

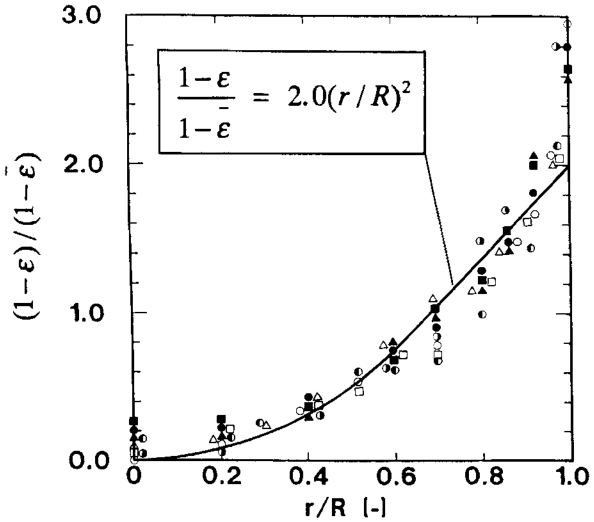
$$(1-\epsilon)/(1-\epsilon_w)=(r/R)^2;\ (1-\epsilon)/(1-\bar{\epsilon})=2(r/R)^2;\quad u_s/u_w=(r/R)^{-3} \tag{14}$$

Discussion and Comparison with Experimental Data

Equation 14 indicates a parabolic radial profile of suspension concentration with the highest concentration near to the pipe wall.

More significantly, Eq. 14 indicates that the radial solids concentration profile is dependent only on the cross-sectional mean solids concentration, and hence is independent of the particular operating conditions, particle and gas properties and equipment scale. Thus, there exists similarity of suspension concentration profile for a gas-particle system operating in the refluxing transport regime.

In Figures 1 and 2 the predicted solids concentration profiles are compared with experimental data from various sources and covering a wide range of operating conditions (superficial gas velocity: 1.4-15.3 m/s); imposed solids flux: (6.6-207 kg/m²·s), pipe diameters (0.032-0.40 m) and particle properties (mean



Key	$\bar{\epsilon}$	2R(m)	U_o (m/s)	G_s (kg/m^{2}s)	Powder
●	0.813	0.090	3.58	89.0	FCC
■	0.813	0.090	3.58	207	HGB
▲	0.813	0.090	3.58	73.6	ALO
○	0.900	0.032	1.40	20.0	FCC
□	0.900	0.090	3.15	29.0	FCC
△	0.900	0.300	2.60	45.0	FCC
◐	0.976	0.090	2.16	8.10	FCC
◑	0.976	0.090	2.16	5.80	HGB

Figure 2. Comparison of theoretical results with experimental data after Tung et al. (1989) in the refluxing dilute—phase transport regime (using air at ambient temperature and pressure).

Powder Details: FCC: mean size—54 μm; particle density—930 kg/m^3; HGB: mean size—75 μm; particle density—608 kg/m^3; ALO: mean size—43 μm; particle density—2,003 kg/m^3.

size range: 32-120 μm; particle density: 1,000-3,500 kg/m^3). It can be seen that the proposed model gives reasonable predictions throughout this range. In particular, the experimental data of Tung et al. (1989), reproduced in Figure 2, give clear confirmation of the prediction of similarity, that is, the systems having the same cross-sectional average solids concentration have identical solids concentration profiles, independent of pipe size, particle properties, superficial gas velocity and imposed solids flux.

The experimental data used in the comparison were judged to be gathered under conditions complying as far as possible with the restrictions of the modeling process (that is, low suspension concentration (< 20% v/v solids), near fully developed flow, small particle size, fluid density ≪ particle density).

Where experimental conditions deviated significantly from those specified above, agreement with the predictions of the model was found to be poorer.

The model also predicts outward radial solids and gas velocities are also predicted in this regime. This outward motion of solids from the core to the annulus has been suggested by recent experimental findings which indicate a decrease in both upward and downward solids fluxes with axial position (for example, Rhodes, 1990).

Conclusions

A simple semi-empirical model is presented for the radial distribution of solids in the upward vertical flow of dilute gas-particle suspensions. This model gives an explanation for the observed core-annulus flow structure in such systems operating in the so-called refluxing dilute-phase transport regime.

The model predicts that the form of the radial solids concentration profile in this regime depends only on the cross-sectional average solids concentration and is hence independent of operating conditions, scale and particle properties.

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Notation

C_1 = constant (Eq. 1)
C_2 = constant (Eq. 6)
d = solid particle diameter
$F_{i,r}$ = interface force, radial component
G_s = solids circulation flux
M = $d^2/[18(1-\epsilon)\mu_f]$
r = radial position variable
R = column diameter
u = component of velocity in r direction
U_o = superficial gas velocity

Greek letters

ϵ = voidage
μ = viscosity
ρ = density

Subscripts

f = fluid phase
s = solids phase
w = at the column wall

Superscripts

$\bar{}$ = averaged cross column radius

Literature Cited

Arundel, P. A., S. D. Bibb, and R. G. Boothroyd, *Powder Technology*, **4**, 302 (1970/71).
Berker, A., and T. J. Tulig, *Chem. Eng. Sci.*, **41**, 821 (1986).
Gajdos, L. J., and T. W. Bierl, Topical Report on work performed under DOE Contract No. EX-C-76-01-2449, Carnegie-Mellon University, Pittsburgh (Sept., 1978).
Geldart, D., and M. J. Rhodes, *Circulating Fluidized Bed Technology*, Basu, ed., Pergamon Press, 21 (1986).
Hartge, E. U., D. Rensner, and J. Werther, *Circulating Fluidized Bed Technology* (*II*), Basu and Large, eds., Pergamon Press, 165 (1988).
Herb, B., K. Tuzla, and J. C. Chen, "Distribution of Solid Concentration in CFB," in *Fluidization VI*, J. R. Grace, L. W. Shemilt, and M. A. Bergounou, eds., Eng. Foundation, New York, p. 65 (1989).
Mineo, H., "High Velocity Circulating Fluidized Beds," PhD Thesis, University of Tokyo (1989).
Rhodes, M. J., "Modelling the Flow Structure of Upward Flowing Gas-Solids Suspensions," *Powder Technology*, **60**, 1, 27 (1990).
Tung, Y., W. Zhang, Z. Wang, X. Lui, and Z. Qin, *Eng. Chem. Met.* (China), **10**(2), 17 (1989).

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