THE HYDRODYNAMIC BEHAVIOR OF PRESSURIZED CIRCULATING FLUIDIZED BEDS

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ABSTRACT

The effects of pressure on the hydrodynamics of circulating fluidized beds (CFB) are investigated using a single, atmospheric, cold laboratory facility with the ability to recycle fluidization gas mixtures of adjustable density and viscosity. By matching five dimensionless parameters, experiments employing plastic powders fluidized with mixtures of sulfur hexafluoride, carbon dioxide and helium achieve hydrodynamic similarity with generic high-temperature CFB risers operating at pressures of 1 and 12 atm. Vertical profiles of static pressure and radial profiles of particle volume fraction are compared in experiments simulating atmospheric and pressurized conditions. These comparisons indicate that gas density plays a surprisingly minor role in the upper portion of the riser where the flow is nearly fully-developed, despite relatively large values of the mean particle Reynolds number.

INTRODUCTION

Pressurized circulating fluidized beds (PCFB) are a promising technology for designing efficient, clean and compact coal combustors. Because PCFBs operate at gas densities an order of magnitude larger than atmospheric units, they should exhibit a markedly different flow behavior. In particular, one might expect a shorter acceleration region at their base and, because higher fluid densities tend to stabilize fluidization, a more homogeneous and steady suspension.

Because of the challenges involved in pressurizing laboratory units, a limited number of academic studies are available in this regime. Plasynski (1991) investigates the pneumatic transport of solids in a tube of 2.6 cm diameter up to pressures of 21 atm. Wirth (1992) reports vertical pressure profiles in a CFB up to 50 atm. Tsukada, Nakanishi and Horio (1993) present similar profiles and radial distributions of solid volume fraction in a CFB of fluid-cracking catalyst operating at 7 atm. While recent progress has been made in the design and operation of industrial pilot-scale PCFBs (e.g., Robertson and Van Hook, 1993), the challenge of performing measurements in these units makes it difficult to understand their hydrodynamics.

To avoid this problem, we employ dimensional analysis to simulate the behavior of pressurized, high temperature conditions in a cold, atmospheric laboratory facility. The idea is to recirculate –rather than discard– fluidization gas mixtures of adjustable density. Atmospheric and pressurized conditions are simulated using, respectively, a light mixture of helium and carbon dioxide, and a denser mixture of carbon dioxide and sulfur hexafluoride. Hydrodynamic analogy between the cold bed and a coal combustor is achieved by matching all relevant dimensionless parameters.

This paper begins with the dimensional analysis and a short description of the experimental facility. We then compare results obtained at high gas densities with previous CFB data for lighter gas mixtures.

DIMENSIONAL SIMILITUDE

In the absence of inter-particle forces or electrostatics, continuum equations for gas-solid suspensions derived, for example, by Anderson and Jackson (1967) yield five dimensionless groups:

$$Fr = u / \sqrt{g \phi d_s} \, , \quad (1)$$

$$M = G / \rho u \, . \quad (2)$$

$$Ar = \rho_S \rho (\phi d_S)^3 g / \mu^2 \, , \quad (3)$$

$$R = \rho_s / \rho \, , \quad (4)$$

$$L = D / \phi d_s \, , \quad (5)$$

The operator sets the Froude number Fr and the solid loading M through the choice of superficial gas velocity u and solid flux G. The Archimedes number Ar and the density ratio R combine gas and solid properties. The dimensionless size L is a measure of the scale of the unit. In these expressions, ρ, μ, and ρ_s are the density of the gas, its viscosity, and the material density of the solids, respectively; g is the acceleration of gravity and D is the riser diameter. Following the suggestion of Chang and Louge (1992), the effective particle diameter is the product of the mean particle Sauter diameter d_s and its sphericity ϕ.

Algebraic manipulations of (1) through (5) relate the operating conditions and properties of the laboratory facility to those in the coal combustor that it models. In this study, we simulate a generic combustor with $\rho_s = 1500$ kg/m^3, $\mu = 4.6.10^{-5}$ kg/m.s and $\phi d_s = 280$ μm. There, the density of hot gases is typically 0.31 kg/m^3 under atmospheric pressure and it is 3.7 kg/m^3 at 12 atm. Properties of the corresponding test suspensions are shown in the Table.

To contrast our “atmospheric” and “pressurized” tests, it is convenient to imagine the two generic coal combustors that this technique simulates. The first operates under atmospheric conditions. The second is pressurized, but runs at the same temperature, superficial velocity and solid flux, and with the same gas and solid composition. Therefore, the two analogous combustors differ mainly through the gas density.

In terms of dimensionless parameters, the “atmospheric” and “pressurized” simulations have markedly different Archimedes number and density ratio. However, they have identical values of the Froude and the ratio $M/R = G/\rho_s u$. Similarly, their dimensionless sizes L are nearly matched. A slight change in L arises from differences in the viscosity of the two test gas mixtures. Because L does not affect dimensionless pressure profiles in atmospheric risers of moderate diameter (Chang and Louge, 1992), this subtlety does not alter the observations that follow.

Test gases					Test powders			Analogous coal unit		
He %	CO_2 %	SF_6 %	ρ kg/m^3	$\mu \times 10^5$ kg/m.sec	type	ρ_s g/cm^3	ϕd_s μm	diameter m	pressure atm	type
92	8	-	0.31	2.0	plastic grit	1.44	162	0.34	1	ACFB
-	60	40	3.54	1.6	plastic grit	1.44	140	0.39	12	PCFB

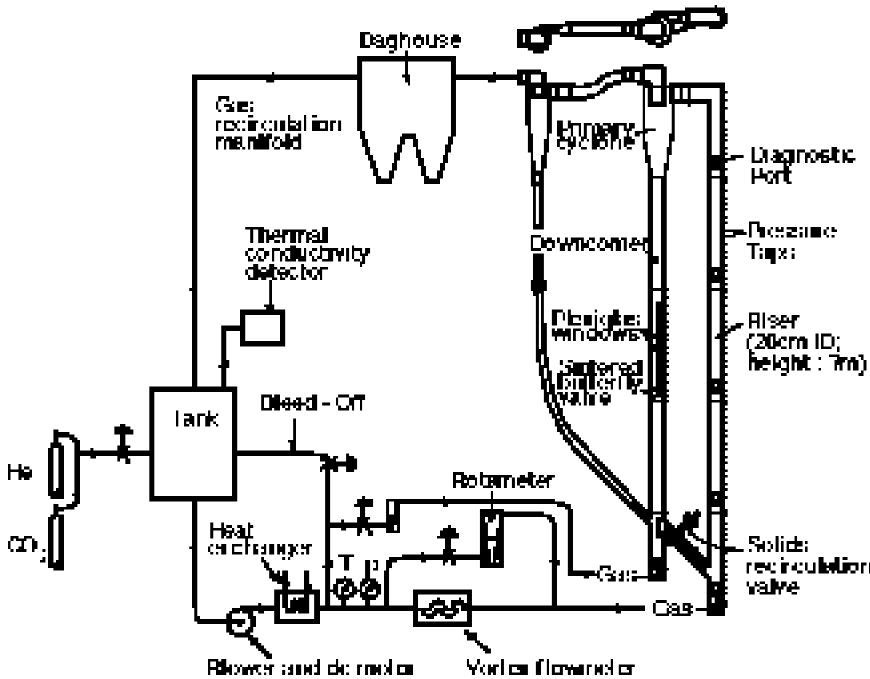

Fig.1. The Circulating Fluidized Bed Facility

APPARATUS

Chang (1991) provides details of the facility sketched in Fig. 1 and its operations. Its unique ability is to recycle any mixture of inert fluidization gases, and thus to set all relevant dimensionless numbers at the desired value. The riser is a vertical column 20 cm in diameter and 7 m high. Two stages of cyclones and a baghouse return clean gases to the blower. In this facility, electrostatics is suppressed by adding approximately 0.5% by weight of Larostat 519, a commercial anti-static salt.

Static pressure is measured using 23 taps mounted flush along the height of the riser. The taps are read in sequence with a scanning valve connected to a single pressure transducer.

Radial profiles of time-average solid volume fraction are recorded with an optical fiber probe (MTI Fotonic 125R) consisting of a group of transmitting and receiving fibers of 0.55 numerical aperture randomly bundled inside an active diameter of 2.2 mm and protected by a 30 cm long stainless steel tube of 3.7 mm diameter. The active diameter is several times larger than the mean particle size to minimize uncertainties in the probe signal (Lischer and Louge, 1992). The optical instrument is calibrated against a quantitative wall capacitance probe (Beaud and Louge, 1995).

RESULTS AND DISCUSSION

In these experiments, we compare the "atmospheric" and "pressurized" vertical profiles of static pressure and the corresponding radial profiles of particle volume fraction for eight simulations with operating conditions in the range $77 \leq Fr \leq 170$ and $0.0011 \leq M/R \leq 0.0052$. In the pressurized tests, this corresponds to loadings of $0.43 \leq M \leq 2.1$. Because the solid recycle leg of the facility limits the solid flux, this relatively modest upper bound for M is the result of the larger gas density of the "pressurized" simulations. Conversely, the lower gas density of the "atmospheric" tests produces loadings at least an order of magnitude larger.

Figure 2 shows a typical vertical profile of static pressure. Here, elevation and pressure are made dimensionless with the riser height H and the product $\rho_s gH$, respectively. As this Figure indicates, the vertical pressure profiles are remarkably similar in the upper part of the riser where the pressure gradient is nearly constant. Because at these relatively high solid concentrations the gradient is balanced by the volumetric weight of the particles, this observation implies that the average solid volume fraction is nearly independent of gas density in the region where the flow is nearly fully-developed.

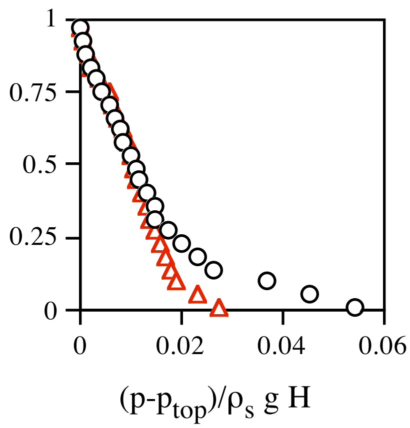

Fig. 2. Comparison of vertical profiles of dimensionless pressure in simulated "atmospheric" (O) and "pressurized" tests (Δ) with Fr = 168 and M/R = 0.0052. The "atmospheric" conditions are L = 1220, Ar = 46, R = 4860 and M = 26; the "pressurized" conditions are L = 1410, Ar = 554, R = 407 and M = 2.1.

In contrast, the profiles diverge in the bottom region where the gas accelerates the particles. As expected intuitively, the denser gas of the "pressurized" tests promotes a shorter acceleration region and thus permits the suspension to reach a fully-developed pressure gradient at lower elevations. Similarly, in the relatively concentrated bottom region, the suspension is more dilute at greater gas densities.

Figures 3 and 4 confirm these observations with radial profiles of solid volume fraction recorded near the bottom of the riser and half-way to the top. As Figure 3 indicates, the radial profiles are nearly independent of gas density in the upper riser. In contrast, the profiles are markedly different in the more concentrated bottom region (Fig. 4). The jagged "atmospheric" profile in Fig. 4 also betrays the unsteady character of suspensions at relatively low gas densities. Unlike the more stable "pressurized" simulations, the "atmospheric" tests are more prone to oscillations in the solid volume fraction, and thus they make it more difficult to produce smooth average radial profiles.

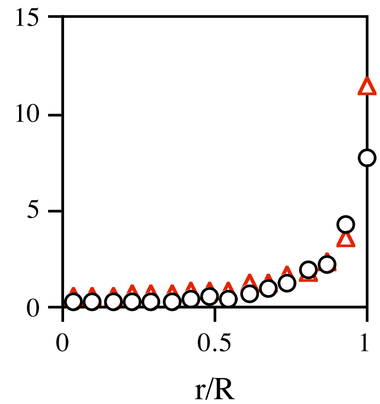

Fig. 3. Profiles of particle volume fraction versus relative radial distance at the elevation z/H = 0.5. By symmetry, only one side is shown. For conditions and symbols, see Fig. 2.

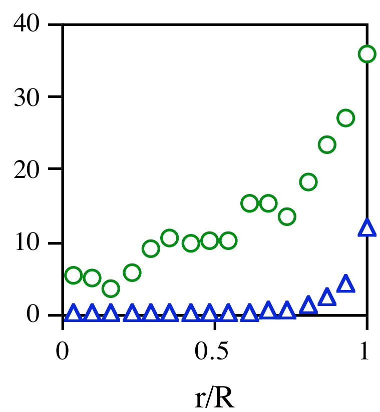

Fig. 4. Radial profiles of particle volume fraction at z/H = 0.2. For conditions and symbols, see Fig. 2.

Our observations in the upper riser suggest a simple interpretation for the momentum balance there. Because at these elevations the flow is nearly fully-developed, the convective terms almost vanish. The momentum equation for each phase thus reduces to a simple balance of forces, which, under the relatively high concentrations of these entrained suspensions, are dominated by the drag force between the two phases, the pressure gradient of the gas, and the weight of the solids. Among these three volumetric forces, the gas density can only affect the drag.

Our measurements of nearly identical volume fractions in the upper riser therefore suggest that the drag is independent of gas density and, consequently, that the interstitial flow lies in the viscous limit, despite relatively large values of the mean Reynolds number Re based on the particle diameter and the superficial gas velocity,

$$Re = u(\phi d_s)\rho/\mu = Fr\sqrt{Ar/R} \ . \qquad (6)$$

For the conditions of Fig. 2, the values of Re are 16 and 195 in the "atmospheric" and "pressurized" tests, respectively.

In contrast, in the lower riser, the gas density appears in the convective terms of the gas momentum balance and, therefore, it can affect the profiles of pressure and voidage, although the interstitial flow may still be dominated by viscous forces.

In a recent study of the effects of gas temperature on the distribution of solids in a CFB riser, Wang, Rhodes and Gibbs (1995) also suggest that the flow may be governed by viscous forces. In their experiments, these authors observe decreasing solid volume fractions as temperature rises between 20°C and 550°C. They argue that, at fixed values of u and G, the decrease in solid volume fraction indicates a smaller mean relative velocity between the two phases and, consequently, a larger drag. Because greater temperatures produce smaller gas densities and greater viscosities, and because the drag grows monotonically with either gas density or viscosity, Wang, Rhodes and Gibbs (1995) gather that the increasing drag can only be attributed to the change in viscosity.

Their conclusions and those of the present work have important consequences for modeling. A common practice is to treat the drag interaction between the two phases as the product of the individual drag on a single particle and a correction based on the local voidage. Because the interstitial flow in the upper riser appears to lie in the viscous limit despite large mean particle Reynolds numbers, this practice seems erroneous. If it was valid, then the magnitude of the Reynolds would be large enough for the gas density to affect the drag and, therefore, to modify the local voidage. Instead, because no such modification is observed, another treatment of the drag should be sought.

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REFERENCES

Anderson, T.B. and Jackson, R., 1967, " A Fluid Mechanical Description of Fluidized Beds - Equations of Motion," *Ind. Eng. Chem. Fundamentals*, Vol. 6, No. 4, pp. 527-539.

Beaud, F. and Louge, M.Y., 1995, "Similarity of Radial Profiles of Solid Volume Fraction in a Circulating Fluidized Bed," Proceedings, Fluidization VIII, J.F. Large, ed., Engineering Foundation, NY, in press.

Chang, H., 1991, "Experimental Investigation of Circulating Fluidized Bed Scale-Up," Ph.D. Dissertation, Cornell University, Ithaca, NY.

Chang, H. and Louge, M.Y., 1992, "Fluid Dynamic Similarity of Circulating Fluidized Beds," *Powder Technology*, Vol. 70, pp. 259-270.

Lischer, D.J. and Louge, M.Y., 1992, "Optical Fiber Measurements of Particle Concentration in Dense Suspensions: Calibration and Simulation," *Applied Optics*, Vol. 31, 5106-5113.

Plasynski, S.I., 1991, "Experimental and Modeling Approach for a High Pressure Vertical Transport Loop," Ph.D. Dissertation, University of Pittsburgh, Pittsburgh, PA.

Robertson, A. and Van Hook, J., 1993, "Circulating Pressurized Fluidized Bed Pilot Plant," Proceedings, Circulating Fluidized Bed

Technology IV, A.A. Avidan, ed., AIChE, NY, pp. 235-239.

Tsukada, M., Nakanishi, D., and Horio, M., 1993, "Effect of Pressure on 'Transport Velocity' in a Circulating Fluidized Bed," Proceedings, Circulating Fluidized Bed Technology IV, A.A. Avidan, ed., AIChE, NY, pp. 209-215.

Wang, X.S., Rhodes, M.J., and Gibbs, B.M., 1995, "Influence of Temperature on Solids Flux Distribution in a CFB Riser," *Chem. Eng. Sci.*, in press.

Wirth, K.E., 1992, "Fluid Mechanics of Pressurized Circulating Fluidized Beds," Fluidization VII, O.E. Potter and D.J. Nicklin, eds., Engineering Foundation, NY, pp. 113-120.