"Fluid Dynamics of Pressurized, Entrained Coal Gasifiers"

Technical Progress Report

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by

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1. Scope

Pressurized, entrained gasification is a promising new technology for the clean and efficient combustion of coal. Its principle is to operate a coal gasifier at a high inlet gas velocity to increase the inflow of reactants, and at an elevated pressure to raise the overall efficiency of the process. Unfortunately, because of the extraordinary difficulties involved in performing measurements in hot, pressurized, high-velocity pilot plants, its fluid dynamics are largely unknown. Thus the designer cannot predict with certainty crucial phenomena like erosion, heat transfer and solid capture.

In this context, we are conducting a study of the fluid dynamics of Pressurized Entrained Coal Gasifiers (PECGs). The idea is to simulate the flows in generic industrial PECGs using dimensional similitude. To this end, we employ a unique entrained gas-solid flow facility with the flexibility to recycle –rather than discard– gases other than air. By matching five dimensionless parameters, suspensions in mixtures of helium, carbon dioxide and sulfur hexafluoride simulate the effects of pressure and scale-up on the fluid dynamics of PECGs. Because it operates under cold, atmospheric conditions, the laboratory facility is ideal for detailed measurements.

These activities are conducted with Air Products & Chemicals, Inc., which is a member of a consortium that includes Foster Wheeler and Deutsche Babcock Energie- und Umwelttechnik AG. This consortium intends to develop and market Second Generation Pressurized Circulating Fluidized Bed (PCFB) technology.

2. Progress

In the seventh quarter of this project, we have interpreted pressure data obtained in the upper region of the riser under a variety of conditions. The interpretation is summarized below. In addition, we have obtained new data from fluidizing glass beads with sulfur hexafluoride. We plan to complete the corresponding experiments in the next quarter of the project.

3. Interpretation of pressure profiles in the upper riser

Our experiments with plastic beads fluidized with a mixture of carbon dioxide and sulfur hexafluoride revealed that the pressure gradients in the upper riser are virtually independent of gas density. This observation encouraged us to interpret the data with a simple, nearly exact model of the fluid dynamics there.

We begin with momentum balances derived, for example, by Anderson and Jackson (1967). Neglecting the weight of the gas phase,

$$\rho \frac{D[\varepsilon u_i]}{Dt} = \frac{\partial}{\partial x_j}(\tau_{ij}) - \frac{\partial[\varepsilon p]}{\partial x_i} - \frac{\rho_p}{T}(1-\varepsilon)\,(u_i - v_i)\,, \qquad (1)$$

where ρ and ρ_p are, respectively, the densities of the gas and the material of the particles, ε is the voidage, p is the gas pressure, u_i and v_i are the velocities of the gas and solids, respectively, τ_{ij} is the gas stress tensor and T is the particle relaxation time. For the solid phase,

$$\rho_p \frac{D[(1-\varepsilon) v_i]}{Dt} = \frac{\partial}{\partial x_j}(S_{ij}) - \frac{\partial[(1-\varepsilon)p]}{\partial x_i} - \rho_p(1-\varepsilon)g + \frac{\rho_p}{T}(1-\varepsilon)(u_i-v_i) \tag{2}$$

where S_{ij} is the solid phase stress tensor and g is the gravitational acceleration.

We assume that the flow is fully-developed, axisymmetric and steady in the upper riser. In this case, the convective terms vanish and Eqs. (1) and (2) reduce to:

$$-\varepsilon\frac{dp}{dz} = \frac{\rho_p}{T}(1-\varepsilon)(u-v) - \frac{1}{r}\frac{d(r\tau)}{dr} \tag{3}$$

$$-(1-\varepsilon)\frac{dp}{dz} = +\rho_p(1-\varepsilon)g - \frac{\rho_p}{T}(1-\varepsilon)(u-v) - \frac{1}{r}\frac{d(rS)}{dr} \tag{4}$$

where z and r are the upward vertical and radial coordinates, respectively, and u and v are the interstitial gas and particle velocities. Note that, because the convective terms vanish, direct dependence on gas density has disappeared from these Eqs. The remaining effects of gas density are limited to the particle relaxation time T.

In order to interpret static pressure measurement, we define the cross-sectional averaging of any hydrodynamic property of interest Ψ as,

$$\bar{\Psi} \equiv \frac{4}{\pi D^2}\int_0^{D/2} \Psi\, 2\pi\, r\, dr, \tag{5}$$

where is and D is the riser diameter. Upon adding Eqs. (3) and (4) and averaging,

$$-\frac{dp}{dz} = \rho_p(1-\bar{\varepsilon})g - \frac{4(S_w+\tau_w)}{D}, \tag{6}$$

where the $S_w < 0$ and $\tau_w < 0$ are shear stresses exerted by the wall on the solid and gas phases, respectively. Because it decreases with D, the contribution of the shear stresses to the pressure drop is negligible in relatively large risers. Thus, we ignore the shear in our analysis and recover the familiar expression for the gas pressure gradient

$$-\frac{dp}{dz} = \rho_p(1-\bar{\varepsilon})g. \tag{7}$$

Note, however, that the shear stresses do not vanish. Adding Eqs. (3) and (4) and subtracting Eq. (7) yields

$$\rho_p(1-\bar{\varepsilon})g = \rho_p(1-\varepsilon)g - \frac{1}{r}\frac{d[r(S+\tau)]}{dr}. \tag{8}$$

Therefore, if S and τ vanished entirely, then $\varepsilon=\bar{\varepsilon}$, which is clearly contradicted by experimental evidence on radial voidage profiles.

For simplicity, we assume that the particle relaxation time is uniform across the riser. Upon averaging the gas momentum Eq., we obtain

$$-\bar{\varepsilon}\frac{dp}{dz} = \frac{\rho_p}{T}\overline{(1-\varepsilon)\,(u-v)}. \tag{9}$$

Eliminating the pressure gradient with Eq. (7), we find

$$\bar{\varepsilon}\ \rho_p(1-\bar{\varepsilon})g = \frac{\rho_p}{T}u\,[(\alpha/\bar{\varepsilon}) - (1+\frac{m}{R})] \tag{10}$$

where $\alpha \equiv \bar{\varepsilon}\ \bar{u}\ /\ \overline{u\ \varepsilon}$ captures radial profiles of the interstitial gas velocity and voidage, m is the ratio of mass flow rates in the solid and gas phases (loading), u is the superficial gas velocity and $R = \rho_p/\rho$. We note that α is a quantity slightly larger than unity. For example, if the profiles of gas velocity and voidage were parabolic, then $\alpha = (4 - \varepsilon_w/\bar{\varepsilon})/3$. In this case, $1 < \alpha < 1.2$.

To evaluate the particle relaxation time T, models of riser flow generally modify the Stokes expression for a single particle ($\rho_p d^2/18\mu$) by employing two corrections. The first, of order ($1+0.15\ Re_p^{0.7}$), extends the Stokes drag to other than low particle Reynolds numbers Re_p; the second, $f(\varepsilon) \sim \varepsilon^{-1.8}$, accounts for the presence of near neighbors,

$$T = \frac{\rho_p d^2/18\mu}{(1+0.15\,Re_p^{0.7})\,f(\varepsilon)}\,, \tag{11}$$

where μ is the gas viscosity, d is the particle diameter and $Re_p \equiv (u\text{-}v)\rho d/\mu$. For convenience, we regroup the corrections into a factor κ and rearrange (10),

$$\bar{\varepsilon}^2 (1-\bar{\varepsilon}) = \frac{\kappa}{St}\left[(\alpha - 1) + 1 - \bar{\varepsilon}(1 + \frac{m}{R})\right], \tag{12}$$

where $St \equiv (\rho_p d^2/18\mu)/(u/g) = \sqrt{R\,Ar}/18Fr$ is a Stokes number representing the ratio of the Stokes relaxation time and a time (u/g) characteristic of flow in the fully-developed region of the riser. In these expressions, $Fr=u/\sqrt{gd}$ and $Ar=\rho_p\rho g d^3/\mu^2$ are the Froude and Archimedes numbers, respectively. Note that, in this fully-developed analysis, the gas density only appears in the correction of the Stokes drag through Re_p.

As Eq. (12) suggests, values of κ and α can be estimated by plotting $Y \equiv \bar{\varepsilon}^2(1-\bar{\varepsilon})St$ against $X \equiv 1 - \bar{\varepsilon}(1+\frac{m}{R})$. Figure 1 shows that all experimental points obtained with "atmospheric" and "pressurized" conditions are grouped on a single straight line with $\kappa \approx 0.14$ and $\alpha \approx 1.006$. Remarkably, κ appears independent of gas density, although the mean particle Reynolds numbers based on the particle terminal velocity are approximately 1.5 and 15 in the atmospheric and pressurized cases, respectively.

These observations suggest that, for all practical purposes, the flow in the upper riser lies in the viscous limit despite large values of the mean particle Reynolds number. Several reasons may be invoked to explain this. First, certain regions of the flow may exhibit values of the mean interstitial slip much lower than the terminal velocity of an individual particle. This may be true, for example, in the descending curtain of solids near the wall or inside particle clusters. It may be that these regions carry a much larger weight in the cross-sectional averaging, thus producing an average drag primarily governed by viscous effects. In this case, our assumption of a uniform drag across the riser should be revisited. Another possible explanation for our observations may be that local regions of the flow are so dense that the appropriate length scale entering the particle Reynolds number is the interstitial distance, which may become much smaller than the particle diameter.

Our intention is to continue interrogating the flow to establish how far the gas density can be increased before gas inertial effects play a substantial role in the upper riser.

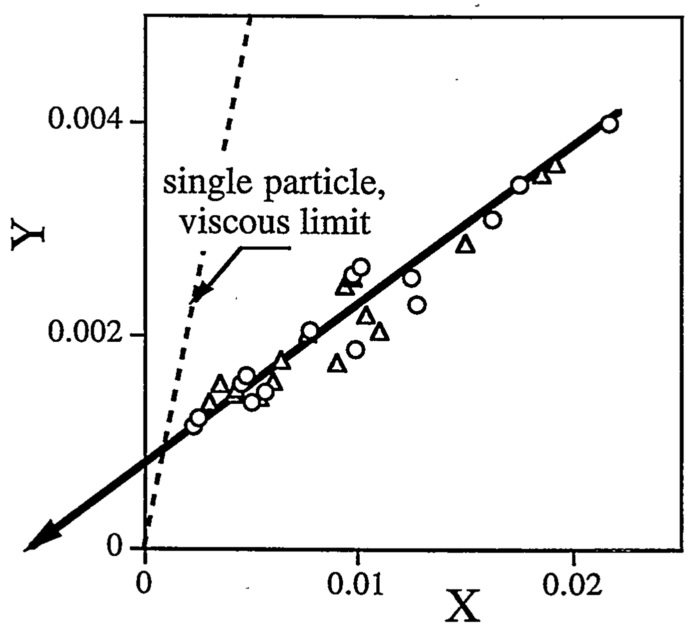

Fig. 1. Plot of Y versus X. The triangles and circles indicate atmospheric and pressurized conditions, respectively. The dashed line represents flows with $\varepsilon \sim 1$ and $Re_p \ll 1$.

4. 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.