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Manuscript received June 8, 1983; revision received August 10, and accepted August 21, 1983.

Coal Particle Suspensions in Vertical Downflow

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Entrained flow reactors, where particles suspended in a gas flow cocurrently through a heated tube, are of considerable interest in coal conversion processes due to their high throughputs. The verticle downward flow orientation (downflow) is of particular interest in such reactors (as compared with horizontal flow or upflow) because of lower total pressure drop and no minimum gas flow rate. Unfortunately, general design correlations for predicting pressure drop and heat transfer characteristics of flowing gas-solids suspensions do not exist for any tube orientation, even for suspensions of uniform, spherical particles. Moreover, data for the downflow orientation are surprisingly scarce, and upflow data are not generally applicable to downflow, as has been shown by Kim and Seader (1983a,b).

Those authors investigated pressure drop and heat transfer characteristics of a suspension of uniform 329-μm glass beads in air, flowing cocurrently downward through a vertical 0.0180-m-i.d. tube. They found the frictional pressure drop to increase with solids loading at a rate significantly lower than is typically reported in the literature for upflow, and the wall Nusselt number to be nearly independent of solids loading. They concluded that transport mechanisms for flowing gas-solid suspensions might be generally weaker in downflow than in upflow.

In this study, data were obtained at similar conditions using suspensions of coal particles. Pressure drop, particle velocity, particle Nusselt number, and wall Nusselt number were determined for fully developed flow, for average particle sizes of 100 and 300 μm. Gas Reynolds number varied from 10,000 to 30,000, and solids loading varied from 0 to 20 kg coal/kg air.

The experimental apparatus, as described by Brewster (1979), consisted of a 7.3-m length of 0.0126-m-i.d. s.s. tubing which was instrumented with 14 pressure taps, and two photomultiplier tubes for determining the velocity of injected particles tagged with phosphorescent powder as described by Brewster and Seader (1980). For heat transfer measurements, a 1.29-m length of tubing at the lower end of the test section was replaced with an identical section which was instrumented with 21 thermocouples for measuring the axial wall temperature profile. The heat transfer section was heated directly by a DC current. In order to insure a fairly constant heat loss for all runs, the maximum wall temperature (near the lower end of the heat transfer section) was adjusted to 366.5 ± 1.1 K, by manually varying the rheostat on the welding unit. This temperature is low enough that significant changes in the coal due to heating were avoided.

A thermocouple sheathed in a s.s. tube was inserted into the suspension at the lower end of the heat transfer section for measuring exit gas temperature. The method of accounting for particle impact-heating and determining the gas temperature has been described by Brewster and Seader (1983). Since this thermocouple quickly eroded, outlet gas temperature was measured for only a few runs.

After checking the system and determining the heat loss with air alone, complete pressure drop profiles were obtained with the larger coal particles to determine whether the test section was long enough to achieve fully developed flow. The profiles appeared asymptotic at the lower end (Brewster, 1979), thus suggesting that the flow was indeed fully developed.

Frictional pressure drop for the region of fully developed flow was calculated from the total measured pressure drop by subtracting the negative contribution due to the solids static head. The *in-situ* concentration of particles was calculated assuming no slip between the particles and gas. This assumption was supported by the results of the particle velocity measurements (particle velocity agreed with gas velocity within experimental error) and by a sensitivity analysis, which showed that the assumption of a slip velocity equal to the free-particle settling velocity does not significantly affect the results.

Frictional pressure drop was correlated in terms of specific pressure drop, defined as the ratio of the frictional pressure drop with solids to that of gas alone flowing at the same velocity. As shown in Figure 1, the frictional pressure drop always increases with increasing solids loading, but the rate of increase is very slow, even slower than that reported by Kim and Seader for glass beads of roughly comparable size. This difference is probably due to entrance effects, since glass beads require a longer acceleration length than coal particles due to higher density and spherical shape.

Particle Nusselt number was determined by heat balance, using the following one-dimensional thermal energy equations for gas and solids:

$$T_p(x) = T_p(0) + \frac{\alpha\beta}{\alpha + \gamma}x - \frac{\alpha\beta}{(\alpha + \gamma)^2}[1 - e^{-(\alpha+\gamma)x}] \quad (1)$$

$$T_g(x) = T_g(0) + \frac{\alpha\beta}{\alpha + \gamma}x + \frac{\beta\gamma}{(\alpha + \gamma)^2}[1 - e^{-(\alpha+\gamma)x}], \quad (2)$$

where α, γ, and β depend on particle Nusselt number Nu_p, particle

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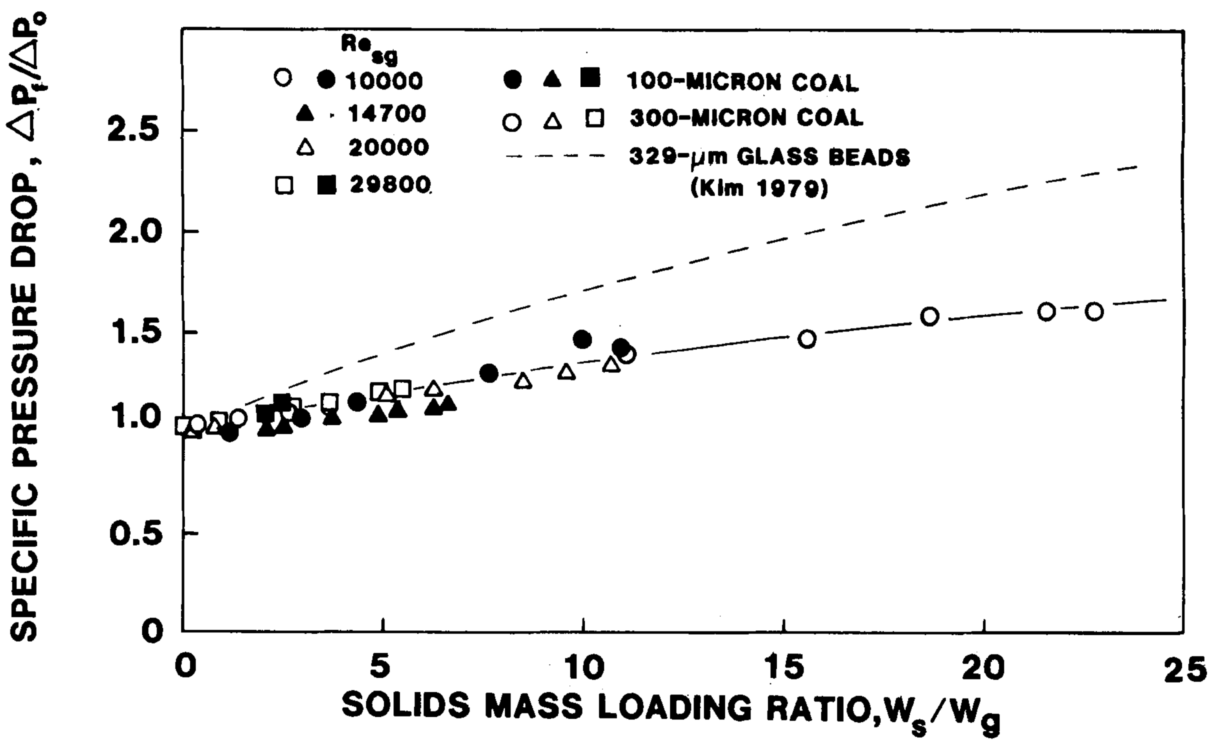

Figure 1. Specific pressure drop ratio.

velocity, other experimental conditions, and physical properties of the gas and solids (Brewster, 1979). The equations were applied to the outlet of the heat transfer section, and the value of Nu_p corresponding to a predicted gas outlet temperature equal to the measured value, was found by trial-and-error. A value of Nu_p was thus determined for each experimental run where gas outlet temperature was measured, Figure 2. Particle Nusselt number was found to decrease significantly with increasing solids loading, reaching values lower than the theoretical minimum value of 2.0 (for a single particle in an infinite, stagnant fluid) for the smaller particle size at high loadings. Admittedly, the correlation shown for the 300-μm particles at the higher value of Reynolds number is arbitrary; it was obtained by forcing the slope to be equal to that of the correlation for the same particles at the lower value of Reynolds number.

Using the straight-line correlations for Nu_p shown in Figure 2 (Nu_p was assumed to have a minimum value of 1.0 for the 100-μm particles), wall Nusselt number, as calculated using Eqs. 1 and 2,

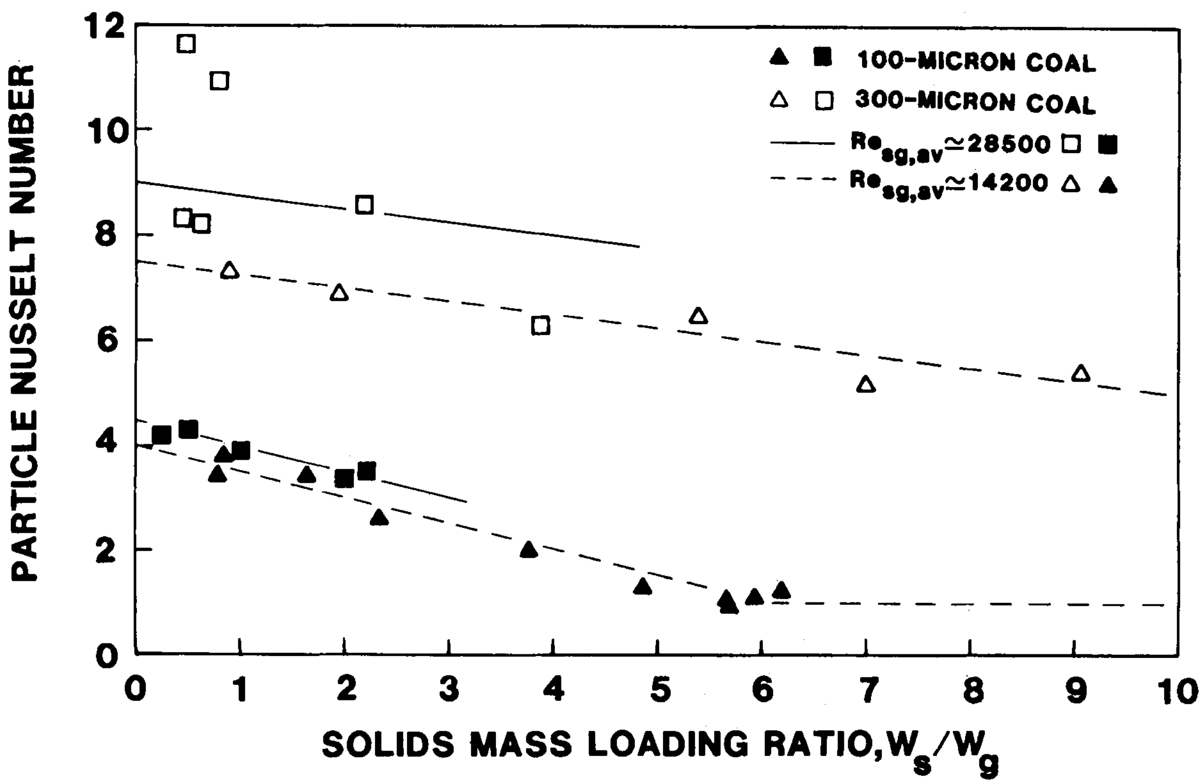

Figure 2. Gas-to-particle heat transfer rate.

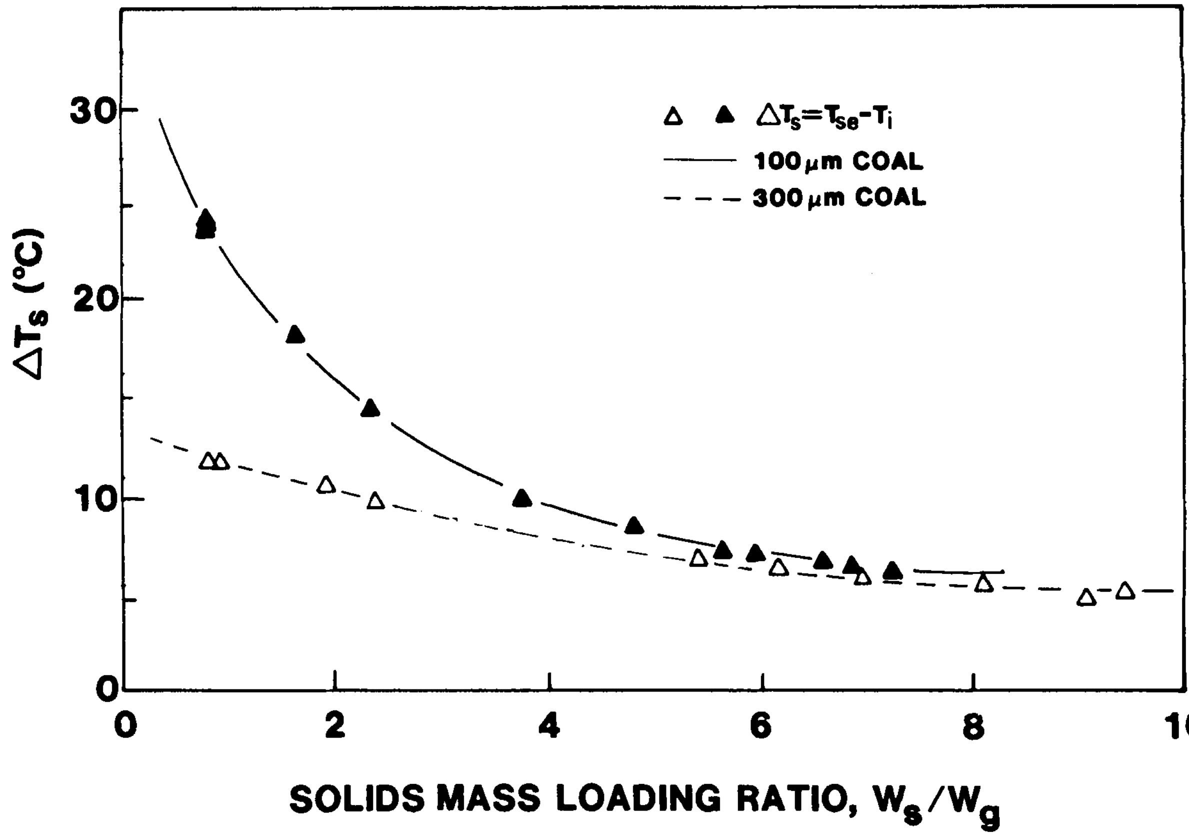

Figure 3. Solids heatup rate.

was found to be independent of solids loading (Brewster, 1979). These findings, together with the findings on the effect of solids loading on frictional pressure drop, confirm the earlier observation of Kim that transport mechanisms may be weaker in downflow than in upflow.

The total temperature rise of solids was calculated for a 14,200 gas Reynolds number, Figure 3, as a function of solids loading. The calculated solids temperature rise is significantly higher for the smaller particles at low solids loading. However, as solids loading increases, this difference becomes insignificant due to the difference in the effect of solids loading on Nu_p for the two sizes of coal. Hence, for a coal reactor being designed to operate at a certain solids loading, there appears to be a lower practical limit for grinding the coal from the standpoint of enhancing heat transfer. Grinding the coal beyond this limit may actually lower the rate of heat transfer and particle heatup.

ACKNOWLEDGMENTS

The authors wish to express appreciation to Ray Cayias, J. M. Kim, W. H. Wiser, and R. E. Wood for many helpful conversations. Financial support was provided by the Department of Energy under Contract E (49-18)-2006.

NOTATION

Nu_p = particle Nusselt number in the suspension, dimensionless
ΔP_o = frictional pressure drop with air alone, Pa
ΔP_f = total frictional pressure drop, Pa
Re_{sg} = superficial gas Reynolds number, dimensionless
$Re_{sg,av}$ = average value of superficial gas Reynolds number
T_g = gas temperature, K
T_p = particle temperature, K
ΔT_s = increase in temperature of the solids passing through the heat transfer section, K
T_{se} = temperature of the solids at the exit of the heat transfer section, K
W_g = mass flow rate of gas, kg/s
W_s = mass flow rate of solids, kg/s
x = distance from inlet of heated tube, m

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Manuscript received August 2, and accepted August 21, 1983.