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Radial and axial profiles of solids loading in a gas-solid circulating fluidized bed

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Numerous chemical processes are run in circulating fluidized beds (CFBs), including fluid catalytic cracking, combustion, and many others (Grace et al., 1997). This paper presents the results of an experimental program in which multiple diagnostic techniques were developed and applied to the flow in a CFB, providing solids volume fractions and their radial and axial distributions.

A pilot-scale gas-solid CFB facility, shown schematically in Figure 1, was designed and fabricated. Solids are fed from the 28-cm inside-diameter (ID) downcomer column through a metering valve and a standpipe into the riser engagement section. The annular engagement section at the riser's base has particles forming a fluidized bed surrounding a central 8.5-cm diameter air supply pipe. Motive air entrains particles from the fluidized bed and transports them up the 14-cm ID riser column to the particle disengagement section. The motive air exits the top of the disengagement section through cyclone separators, which return particles to the downcomer. The motive air and any remaining particles exit the cyclones and are vented to atmosphere through a HEPA filter baghouse. Fluidization air is supplied at the bases of the downcomer, the engagement and disengagement sections; and in the solids transfer standpipes.

The riser has a total uniform length of 5.77 m, or an aspect ratio of L/D ~ 41. This length measurement excludes the 54.6-cm high engagement section, the top of which defines the axial origin z = 0. The overall length of the downcomer is 4.27 m. Most of the riser is fabricated from clear acrylic with PVC fittings. The annular design of both the engagement and disengagement sections ensures that the flow in the vertical riser is as axisymmetric as possible. The riser is extensively grounded and the inlet air humidified to reduce triboelectric effects.

The riser is loaded with equilibrium fluid catalytic cracking (FCC) catalyst particles of density 1250 kg/m^3 and Sauter mean diameter 65 microns. Solids flux is measured using a diverter valve section that allows fast capture, weighing, and return of particles to the system.

Differential Pressure (ΔP) measurements are made by instrumenting the entire flow loop using electronic transducers (Validyne DP15). Sixteen transducers are installed at 30.5-cm intervals along the riser length. Reference (gage) pressures are acquired at one location in the riser, at the tops of the disengagement and downcomer, and on the air supply and outlet lines. Sintered metal discs (10-micron nominal pore size) protect the transducers from contamination by catalyst. These discs are installed flush with the interior wall of the riser. The presence of these in-line filters limits the frequency response of the transducers to about 1 Hz. The DP signals are converted to volume-averaged solids loading using the hydrostatic assumption.

The **Gamma Densitometry Tomography (GDT)** system (Figure 2) consists of a 100-mCi ^{137}Cs source and an array of 8 NaI(Tl) scintillation detectors. The source produces a fan-shaped beam that passes through the riser to the detector array, where the gamma intensity along each distinct ray is measured. The source and detectors are mounted on a vertical traverse that allows measurement along the riser axis, and the detectors are mounted on a separate lateral traverse that allows lateral displacement of the detectors, with the source fixed, in order to achieve improved spatial resolution for near-wall measurements. Each scintillation detector (Bicron Model 2M2/2, run at 900 V DC) is connected to an Ortec® ACE Mate™ 925-SCINT amplifier and bias supply, which amplifies and shapes the detector pulses, then to an Ortec® 916A multichannel analyzer (MCA). Ortec® Maestro software is used to collect data from the 8 detectors simultaneously. The complete energy spectrum is measured by the MCA, and the counts around the 662 keV peak are used in the analysis presented below.

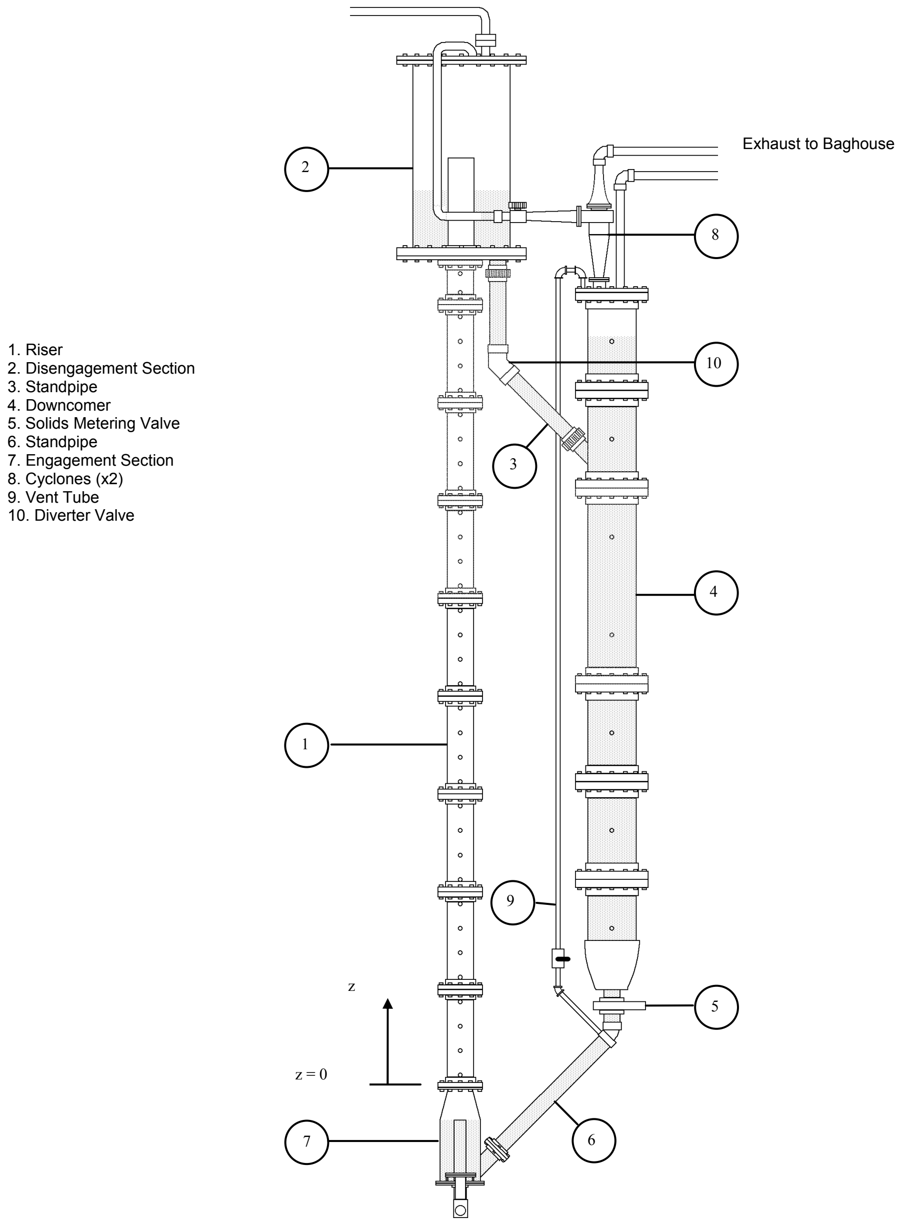

Figure 1. Schematic of gas-solid circulating fluidized bed.

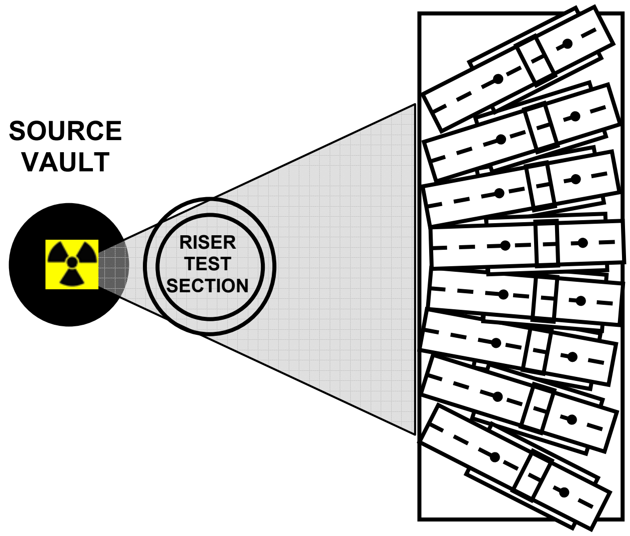

Figure 2. Gamma tomography system layout. Source is 100-mCi ^{137}Cs.

Attenuation of monoenergetic gamma photons is given by $I = I_o e^{-\mu L}$, where I is the measured intensity, I_o is the unattenuated "empty" intensity, μ is the attenuation coefficient, and L is the path length through the solid material. For measurement of multiphase mixtures for which the attenuation coefficient μ is not known, the amount of attenuating material in the beam path can be determined by using a ratio between empty and full measurements.

The fraction of full solids volume fraction is given by

$$\frac{L}{L_{full}} = \frac{\ln(\frac{I}{I_0})}{\ln(\frac{I_{full}}{I_0})}$$

For these experiments the values of I, I_{full}, and I_o were taken from the peak intensity region of the full energy spectrum measured using the MCA. At least 10^4 counts were recorded around the 662 keV peak in order to achieve 1% or better uncertainty due to inherent Poisson statistics of the gamma source (uncertainty = $N^{-1/2}$). Typical acquisition time is 30 seconds at each position.

A generalized Abel transform (Vest, 1985; Shollenberger, 1997) that allows asymmetric phase distributions is used to convert the path-averaged solids volume fraction into a radial solids volume fraction profile in the circular domain. Figure 3 includes representative radial profiles of solids fraction measured using GDT.

A 16-electrode **Electrical Impedance Tomography (EIT)** system was developed and is described in detail by Tortora (2004). Electrodes are supplied with a 100 kHz, 5 V driving frequency, and impedance is measured between electrode pairs. Reconstruction is performed using an optimization code to determine the best values of local solids fraction to yield the measured impedances, using the Rayleigh mixture model to relate impedance to solids fraction. Figure 3 includes representative radial profiles of solids volume fraction measured using EIT.

RESULTS

Table 1 lists the four flow conditions examined in this work. Superficial gas velocity and solids flux were varied. Figure 3 shows representative radial profiles of solids volume fraction for each flow condition measured at z/D = 12. As is common in these flows, a core-annular flow structure is indicated, with higher solids volume fraction at the walls and lower in the center.

	Superficial Gas Velocity U_g (m/s)	**Solids Flux G_s ($kg/m^2 \cdot s$)**
Case 1 (low gas, low solids)	5.34 ± 0.07	60.4 +/- 4.8
Case 2 (high gas, low solids)	7.34 ± 0.06	55.7 +/- 4.8
Case 3 (low gas, high solids)	5.41 ± 0.06	64.2 +/- 3.8
Case 4 (high gas, high solids)	7.44 ± 0.07	66.6 +/- 4.3

Table 1. Test conditions. Uncertainty includes run-to-run variations.

Figure 4 shows axial profiles of the volume-averaged solids volume fraction determined by GDT, EIT, and ΔP for each of the four flow conditions given in Figure 4.

The ΔP profiles in Figure 4 were constructed by picking the ΔP points recorded simultaneously with the GDT data and interpolating between the nearest two axial ΔP locations. Conditions (U_g and G_s) were held nominally constant within each series of runs. Each of the four runs shown in Figure 4 was actually run over a several day period. Run conditions were always brought back to the same nominal settings.

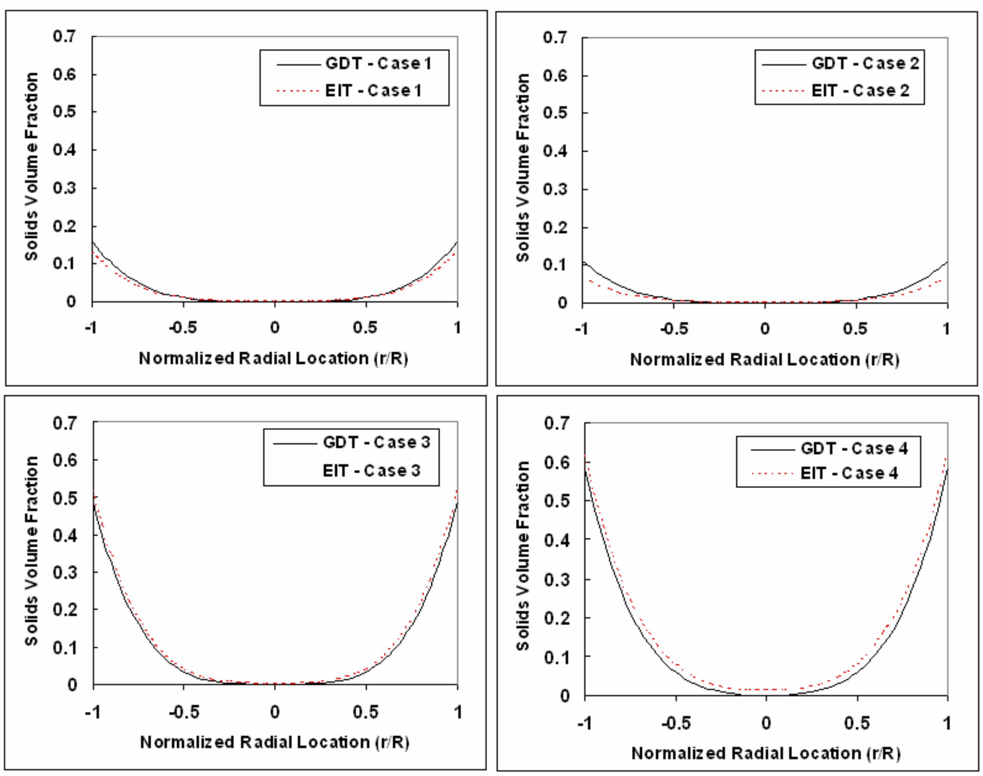

Figure 3. Radial profiles of solids loading as measured by GDT and EIT methods. Flow conditions are given in Table 1.

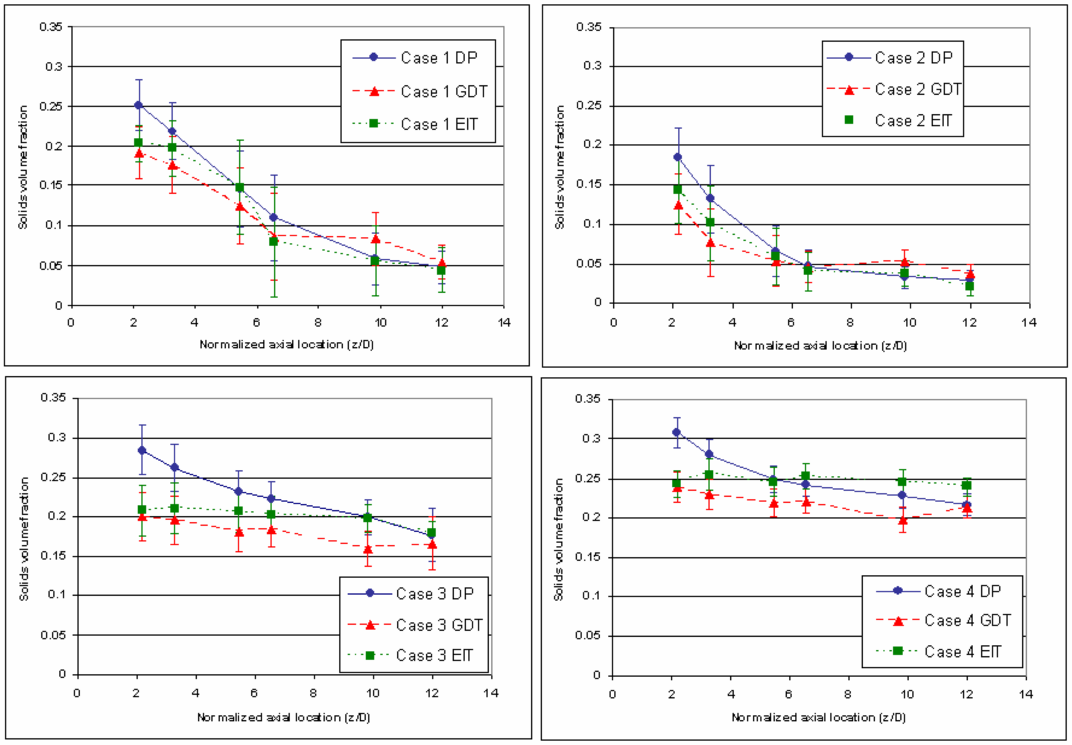

Figure 4. Axial profiles of solids loading as measured by ΔP (DP in legends), GDT, and EIT methods. Flow conditions are given in Table 1.

DISCUSSION

Comparison of the GDT, EIT and ΔP-determined solids loading is shown in Figure 4. Recall that ΔP is volume averaged, while GDT and EIT are area-averaged. For the purposes of this comparison, all were time-averaged for five minutes. The data of Figure 4 indicate that the ΔP-determined values are higher than the GDT and EIT values low in the riser. This is as predicted by Louge and Chang (1990), since the flow is not fully developed near the base of the riser resulting in significant gradients in solids loading.

The data show similar trends to those of Schlichthaerle and Werther (1999), even though the present solids fluxes are much higher and the axial region scanned extends much further up the riser. The Schlichthaerle and Werther data indicate that even at low solids flux the effect of solids loading gradients is still important at the base of the riser. Louge (1990) also presents data showing similar behavior at even higher solids fluxes (up to 600 $kg/m^2 \cdot s$).

CONCLUSIONS

Experiments were performed to compare the solids volume fraction measured by GDT, EIT, and ΔP techniques over a range of CFB operating conditions. The GDT and EIT results show good agreement for both radial and axial solids-volume-fraction profiles. The present data support the analysis of Louge (1990) and the experimental data of Schlichthaerle (1999) and extend this comparison to higher solids fluxes and axial distances along the riser. The ΔP technique is complicated low in the riser by the effects of solids flux and gradients of solids volume fraction and thus overpredicts the true solids loading. Higher in the riser the ΔP data come into general agreement with those of GDT and EIT.

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