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COMPARISON OF GAMMA-DENSITOMETRY TOMOGRAPHY AND ELECTRICAL-IMPEDANCE TOMOGRAPHY FOR DETERMINING MATERIAL DISTRIBUTION IN LIQUID-SOLID FLOWS*

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ABSTRACT

Gamma-densitometry tomography (GDT) and electrical-impedance tomography (EIT) have both been applied to a liquid-solid flow for comparison purposes. The experiment consisted of a cylinder (19 cm diameter) filled with water, in which 80 μm glass spheres were suspended by a mixer to achieve solid volume fractions of 0.01, 0.02, and 0.03. Both GDT and EIT revealed a relatively uniform distribution of solids in the measurement plane, and the average solid volume fractions from both techniques were in good agreement.

NOMENCLATURE

R	=	radius of cylindrical vessel
x	=	horizontal position, $x = 0$ at cylinder axis
ε_s	=	solid volume fraction (unitless)
μ	=	gamma attenuation coefficient (cm^{-1})
σ	=	electrical conductivity ($\Omega^{-1}m^{-1}$)
$(\ )^{EIT}$	=	electrical-impedance tomography
$(\ )^{GDT}$	=	gamma-densitometry tomography
$(\ )^{NOM}$	=	nominal value
$[\ ]_{av}$	=	average over measurement plane
$(\ )_m$	=	pertaining to mixture
$(\ )_s$	=	pertaining to glass spheres
$(\ )_w$	=	pertaining to water

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INTRODUCTION

The spatial distribution of materials in multiphase flows is of importance to many industrial processes. For example, in indirect coal liquefaction, a reactive gas is bubbled through a catalyst-laden liquid (slurry), and a spatially nonuniform gas distribution can reduce process efficiency by inducing large-scale buoyancy-driven recirculating flows (cf. Jackson et al., 1996). Gamma-densitometry tomography (GDT) and electrical-impedance tomography (EIT) are techniques with the potential of providing spatially resolved information on material distribution in multiphase flows. At present, GDT is a fairly mature technology (cf. Hewitt, 1978), whereas many issues still remain to be resolved for EIT, particularly as applied to multiphase flows (cf. Yorkey et al., 1987; Jones et al., 1993; Lin et al., 1993; Ceccio and George, 1996). The purpose of the present study is not to develop new GDT or EIT algorithms but rather to compare existing GDT and EIT techniques (Shollenberger et al., 1995; Adkins et al., 1996; Torczynski

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et al., 1996ab; O'Hern et al., 1995) when applied to the same multiphase flow. Unlike the work of Lin et al. (1993), the emphasis here is not on the accurate determination of interfaces between phases. Instead, the medium under consideration is assumed to have smoothly varying mixture properties when averaged over length scales large compared to the size and separation of the dispersed-phase regions but small compared to the extent of the medium.

A liquid-solid flow has been examined with both GDT and EIT. A flow of particle-laden liquid was chosen for investigation for several reasons. First, the amount of solid introduced into the experiment can be carefully controlled and, for a closed volume, remains constant for all time. Knowledge of the average solid volume fraction thus provides a good check on the diagnostics. Second, unlike gas bubbles, solid particles can be small, uniform-diameter spheres that do not deform or otherwise change their shape during the experiment (so long as conditions are not harsh enough to fracture the particles). Third, a mixer can be employed to generate a relatively uniform distribution of solids throughout most of the flow geometry. Fourth, the solid particles and the liquid medium can be chosen without difficulty to have significantly different gamma attenuation coefficients and electrical conductivities so that both GDT and EIT can be applied. Fifth, each technique by itself should be capable of determining the solid volume fraction. Since the GDT system has already undergone extensive application to multiphase flows (Shollenberger et al., 1995; Adkins et al., 1996; Torczynski et al., 1996a), it can be used to assess the behavior the EIT system for multiphase-flow measurements, which had previously been applied only to single-phase systems into which an insulating object of known dimensions had been inserted (O'Hern et al., 1995; Torczynski et al., 1996b).

EXPERIMENTAL SETUP

Schematic diagrams of the experimental setup and diagnostics are shown in Figures 1-3. The flow apparatus consisted of a Lexan cylinder (19 cm inner diameter, 0.635 cm wall thickness, 76 cm height, see Figure 1) closed at the bottom and the top, into which a mixer was inserted. A Sargent-Welch mixer (model S-76509-80B) was used. The mixer system consisted of a compact impeller assemblage positioned 1 cm above the bottom of the cylinder interior, a motor mounted above the top end of the cylinder, and a shaft (0.8 cm diameter with the coating, described below) connecting the impeller to the motor. The shaft passed through a small concentrically-positioned hole in the top end of the cylinder, around which an "overflow" volume was placed to ensure the absence of free-surface effects (e.g. a vortical "funnel" due to swirling) in the cylinder interior during mixing. A mixer speed of 600 rpm was used for all solid volume fractions, as needed to achieve a roughly uniform distribution (to the eye) of particles within the liquid. For solid volume fractions much in excess of 0.03, large fluctuating motions and solid volume fraction variations were visually apparent, so solid volume fractions were restricted in this study to no larger than about 0.03 although even at this value some solid volume fraction variations were discernible.

The nominal (volume-averaged) solid volume fraction ε_s^{NOM} was specified in the following manner. Glass spheres with a mean diameter of 80 μm were used. A prescribed volume of these spheres, as determined by weight and the known density of the glass, was introduced into the cylinder, and water was added until the remaining volume was filled. Water was selected because its electrical conductivity can be adjusted by dissolving a small known amount of salt (sodium chloride) in it. Typical electrical conductivities of the salt-water solution were around 1 mS/cm. However, temperature variations and their effects on the precise ionic composition of water were large enough to alter the conductivity appreciably, necessitating the calibration measurements discussed below. Glass spheres were selected for the following reasons. First, they are fairly rugged and are easily separated from water by settling. Second, glass is an insulator compared to (non-deionized) water, so EIT can in principle discriminate between glass spheres and water. Third, glass attenuates gamma photons more strongly than does water, so GDT can also discriminate between glass and water.

The precise details of GDT and EIT (see Figures 2-3 for schematic diagrams) have been discussed elsewhere (Shollenberger et al., 1995; Adkins et al., 1996; Torczynski et al., 1996ab; O'Hern et al., 1995). In brief, GDT measures the average attenuation of a multiphase region along several chords intersecting the region, and EIT measures the voltages at many electrodes positioned around the perimeter of the multiphase region when a prescribed current is passed from one electrode to another through the region. For each technique, a tomographic reconstruction algorithm is used to determine the material distribution giving rise to the measured quantities. In the reconstruction algorithms employed in this study, only radial variations in the material distribution are allowed, which is reasonable for this experiment and greatly facilitates the reconstruction. For GDT, a 5 Curie cesium-137 source produces 0.6616 MeV gamma photons, which are subsequently detected by a sodium iodide detector. All chords are chosen to lie in the midplane of the cylinder (see Figures 1-2) and to all be parallel with a 1 cm spacing, and counts were collected for 10 s along each chord. For EIT, a 50 kHz current supply was used to excite

Table 1: Experimental conditions and analysis results.

Case	Description	ε_s^{NOM}	$[\mu_m/\mu_w]_{av}$	ε_s^{GDT}	$[\sigma_m/\sigma_w]_{av}$	ε_s^{EIT}
1	mixed solid-liquid	0.010	1.015	0.011	0.982	0.012
2	mixed solid-liquid	0.020	1.030	0.021	0.968	0.021
3	mixed solid-liquid	0.030	1.057	0.040	0.940	0.041

16 point-electrodes, which were 3-mm-diameter disks penetrating the cylinder wall at equal azimuthal increments around the midplane perimeter (see Figures 1 and 3). Each experiment is the average of 64,000 repetitions of each measurement at each electrode and takes 10 minutes to acquire.

The presence of the mixer shaft is somewhat problematic for both techniques. For GDT, it produces extra attenuation when the gamma beam passes through it. In this study, these anomalous points are not used in performing the reconstruction. For EIT, placing a good conductor like the mixer's steel shaft in the center of the cylinder would significantly distort the electric field lines, so the shaft and impeller were coated with a layer of insulating paint to mitigate this effect. The presence of a small-diameter (relative to the cylinder), concentrically-positioned, insulated inclusion was expected to have only a small effect on the electrical behavior of the system, and this was verified by taking EIT measurements using water (no particles) both with and without the mixer shaft.

EXPERIMENTAL RESULTS AND ANALYSIS

Three sets of experiments were performed in this study, as summarized in Table 1. In each set, a prescribed amount of glass spheres was introduced to the cylinder, and the remainder of the volume was filled with water. Mixing was then initiated for a 30-minute period, which was determined to be long enough for the system to come to a statistically stationary state. GDT and EIT were successively applied, as discussed above, where the GDT and EIT scans required 4 and 10 minutes, respectively. Mixing was then terminated, and the solid-liquid mixture was allowed to remain quiescent for a 5-minute period, which was long enough for the spheres to settle to the bottom of the water-filled cylinder. Following this settling period, EIT was applied again. This second EIT measurement was necessary for calibration purposes because the conductivity of the water was altered by soluble contaminants unavoidably introduced when the spheres were added. Although this trace amount of contaminant material had a negligible effect on GDT, as verified by additional GDT measurements, its effect on the water conductivity was comparable in magnitude to that of the suspended solid particles during mixing.

Figure 4 shows a plot of μ_m/μ_w, the chordal average of the mixture attenuation coefficient normalized by the attenuation coefficient of water, as a function of x/R, the normalized horizontal position of the measurement chord, as determined by GDT for the solid-liquid cases delineated in Table 1. The data points at $x = 0, \pm 1$ cm are anomalous because the gamma beam passes through or near the mixer shaft and are not shown. Several observations can be made from this plot. First, despite some variations due to the unsteady nature of the flow, the profiles are relatively uniform. Second, the normalized mixture attenuation coefficient increases monotonically with increasing nominal solid volume fraction. A previously described GDT reconstruction algorithm (Shollenberger et al., 1995) was used to determine the average normalized mixture attenuation coefficients for these cases, as shown in Table 1 and Figure 4. In these calculations, the attenuation coefficient profile was taken to be spatially uniform. Additional calculations performed using radially parabolic profiles were found to yield almost identical profiles and averages (the reconstructions were not improved significantly in quality by the additional degree of freedom). To convert the mixture attenuation coefficients to the solid volume fractions shown in Table 1, the following relation was used:

$$\varepsilon_s^{GDT} = \frac{[\mu_m/\mu_w]_{av} - 1}{[\mu_s/\mu_w] - 1}, \qquad (1)$$

where the attenuation coefficients of water and the glass spheres are given by $\mu_w = 0.0858$ cm^{-1} and $\mu_s = 0.209$ cm^{-1}, which were previously measured (Torczynski et al., 1996a).

A previously described EIT reconstruction technique (O'Hern et al., 1995; Torczynski et al., 1996b) is applied to determine the electrical conductivity of the multiphase flow. In brief, the electrical conductivity distribution is represented as a parametrized function of position, and these parameters are adjusted according to a Newton-Raphson scheme to minimize

the rms difference between the measured voltages and those computed using a (three-dimensional) finite-element solution of the voltages for given values of the conductivity parameters. The commercial code FIDAP (Fluid Dynamics International, 1995) was used to generate the finite-element solutions. Nearly identical average conductivities were obtained when using either a spatially uniform conductivity distribution or a radially parabolic distribution (as also observed for GDT), so a uniform distribution was employed, being simpler and equally accurate for this experiment. Table 1 shows $[\sigma_m/\sigma_w]_{av}$, the average electrical conductivity of the mixture normalized by that of the liquid. The mixture electrical conductivity is seen to decrease monotonically with increasing nominal solid volume fraction, as expected. To convert the normalized mixture electrical conductivities to the solid volume fractions shown in Table 1, the Maxwell-Hewitt relation for a purely resistive medium with small insulating spheres dispersed randomly throughout was used (Hewitt, 1978; Ceccio and George, 1996):

$$\varepsilon_s^{EIT} = \frac{1 - [\sigma_m/\sigma_w]_{av}}{1 + (1/2)[\sigma_m/\sigma_w]_{av}}. \qquad (2)$$

The solid volume fractions determined by GDT and EIT are seen to be in close agreement with each other for all cases (see Figure 5) and with the nominal values for the first two cases. Case 3 is interesting in that the GDT and EIT values are in agreement with each other but are somewhat higher than the nominal value. It is conjectured that the mixing may not have been strong enough to produce a uniform axial distribution of glass spheres throughout the cylinder for a nominal solid volume fraction of 0.03 so that the solid volume fraction was less than the nominal value near the top of the cylinder and larger below.

CONCLUSIONS

Gamma-densitometry tomography (GDT) and electrical-impedance tomography (EIT) have been applied to study a suspension of glass spheres in water. For the solid volume fractions examined, both techniques indicated relatively uniform distributions of particles in the measurement plane and yielded average values that agreed closely with each other. Good agreement was also found with the nominal value of the solid volume fraction for all cases except for the highest value. In this case, the GDT and EIT values were in agreement but somewhat larger than the nominal value, suggesting that mixing in this case was not strong enough to overcome buoyancy-driven stratification and produce a uniform distribution of the solid. Future work will focus on several areas: hardware and software refinements, examination of more concentrated suspensions, production of radially nonuniform distributions via swirling flow, and application to gas-liquid and gas-liquid-solid flows.

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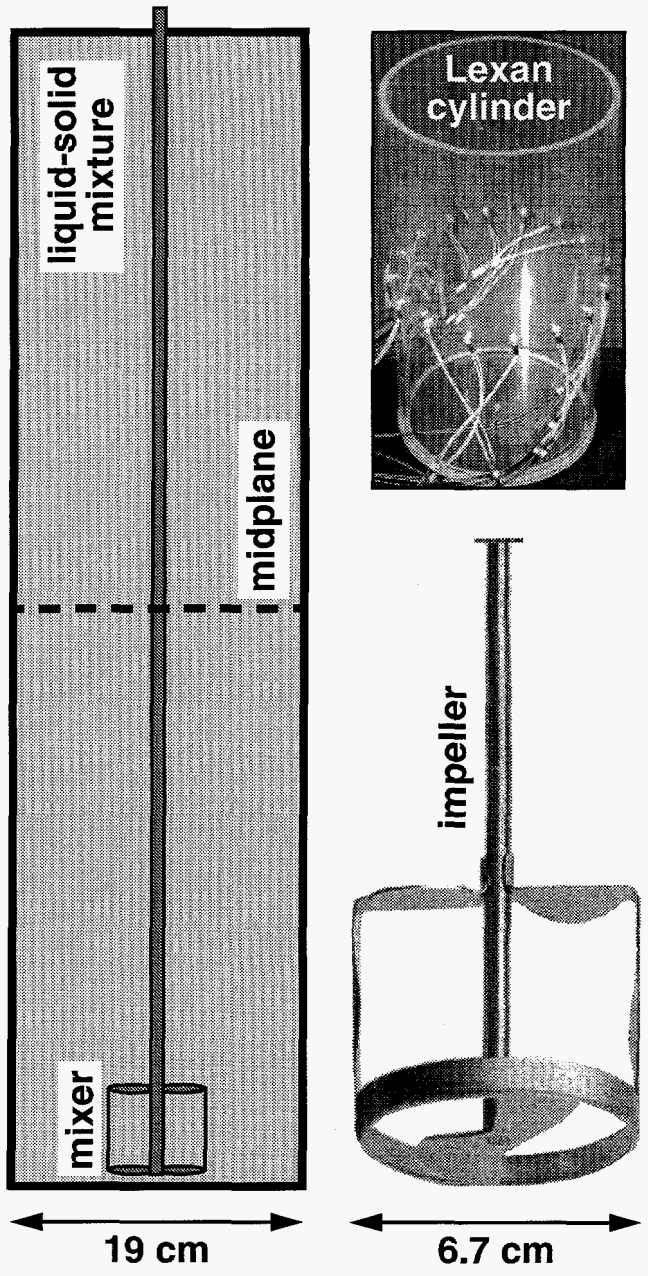

Figure 1. Left, liquid-solid-flow experiment. Top right, Lexan cylinder without mixer but with EIT electrodes. Bottom right, impeller.

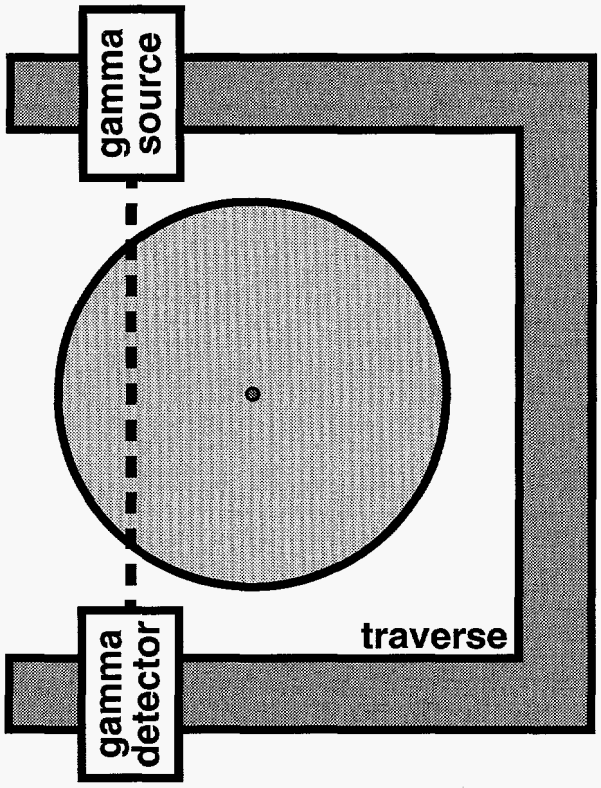

Figure 2. Gamma-densitometry tomography (GDT).

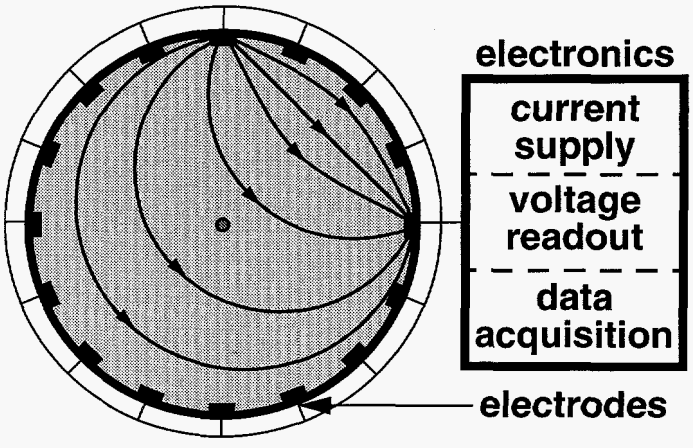

Figure 3. Electrical-impedance tomography (EIT).

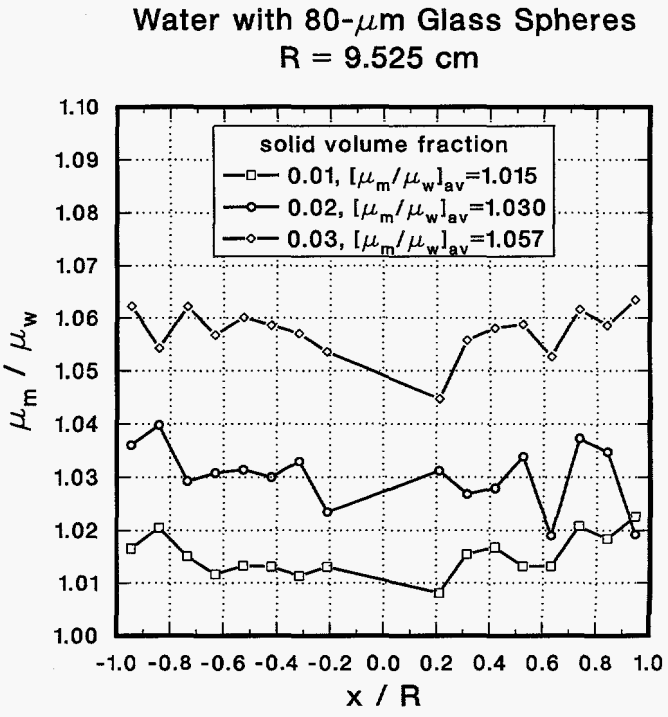

Figure 4. Mixture attenuation coefficient from GDT.

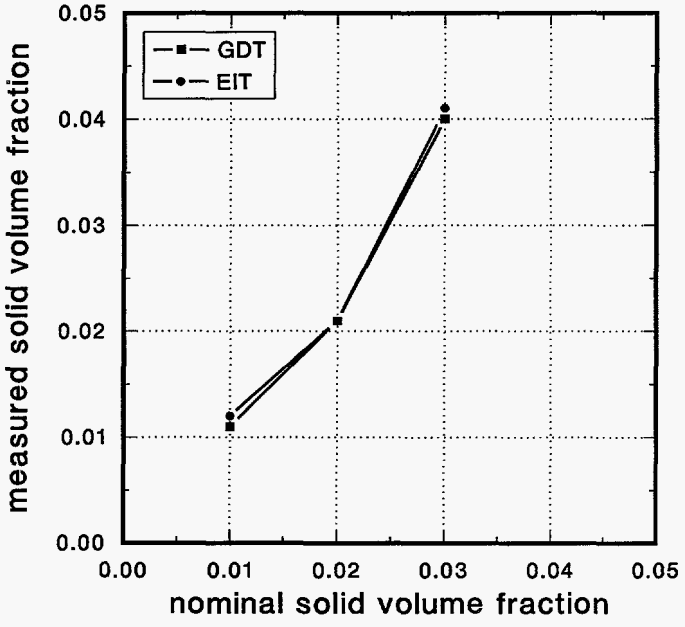

Figure 5. Solid volume fractions from GDT and EIT.