Tomographic Measurements of Granular Flows in Gases and in Liquids†

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Abstract

Two distinct non-intrusive radiation methods known as scanning gamma ray tomography and single profile photon absorptiometry are presented in this paper as tools for the investigation of interstitial voidage distributions of granular flows in both gases and liquids. Single profile absorptiometry coupled with the consecutive radial transformation of the linear data obtained within seconds of flow time is used as a tomographic tool for dynamic voidage characterization in different flow regimes of air and liquid-based systems, as well as a complete tomographic projection procedure, which requires scan times of the order of minutes to achieve high spatial resolutions over a large cross-sectional area of the vessels. A novel tomographic technique currently under development known as dual photon tomography is proposed to facilitate simultaneous voidage mapping and particle tracking in 3-D granular flows.

1. Introduction

Various problems arise during the transport and handling of granular materials in the process industry. Particle segregation and attrition, lack of control in solids flow rates, build-up of adverse pore pressures are some of the major problems. It is a common belief that most of these problems are closely linked to the behaviour of the interstitial voidage within the process units. The need therefore emerged for reliable quality control methods, and a considerable amount of the research pursued during the last ten years in the particle technology area has been focused on the investigation and application of these methods. Based on various physical principles (nuclear emission, magnetic resonance, electrical impedance), these methods were already in use in other fields such as medicine, chemistry and biology with established success. The main consideration in choosing the appropriate method for characterizing the bulk voidage profiles in a granular system is the need for achieving the necessary spatial resolution, and in the case of dynamic events, the appropriate temporal resolution is also important.

Gamma ray tomography was one of the first non-invasive techniques used to investigate the two-phase flow behavior of single or multicomponent granular systems. The investigation of the voidage structure near the jet region of a fluidized bed and the effects of background fluidization and particle shape on the dissipation of the gas momentum in this region were first reported by MacCuaig et al. (1985)12.

By using the same tomographic equipment, Seville et al. (1986)16, investigated the jet and the bubbling region of a fluidized bed above a multi-orifice distributor and determined the transition height between them. All the results were in very good agreement with several previous theoretical predictions and other experimental methods. The tomographic scanner used for this work provided time-averaged profiles over a long period (6-7 hours) with a spatial resolution of 5mm.

A new tomographic facility now in use at Surrey opened new perspectives in the study of granular systems by meeting both the spatial and the temporal resolution requirements simultaneously. A preliminary work in gas-based granular systems is reported by Hosseini-Ashrafi and Tüzün (1993)9, where consecutive scans at various heights of a hopper housing mono-sized and binary mixtures during start-stop experiments revealed a maximum value of voidage near the orifice propagating with time up the conical section of the hopper. The voidage values obtained from the gamma ray scan showed close agreement with published theoretical values, and their transformation in polar coordinates (both angular and annular)
proved the axial symmetry inside the hopper.

The axial symmetry inside the hopper enabled the development of a new technique (Hosseini-Ashrafi and Tüzün, 1993)\(^{10}\), which offers considerably faster scans without sacrificing the spatial resolution. The new technique employs single photon absorptiometric profiles across the hopper within a few seconds, retaining a spatial resolution of 1 mm necessary for quantifying the interstitial voidage, and consecutive transformation of the Cartesian data to polar coordinates resulting in a radial distribution of the density function. The main advantage of this technique is that tomographic information can be extracted from the single profile measurements in a shorter time period than if a complete scan were performed.

Work concerning the application of gamma ray tomography in spouted beds (a variant of a fluidized bed where gas enters the bed from a single orifice) is reported by Simons et al. (1993)\(^ {17}\). The quantitative analysis of the raw data showed a higher central voidage region in the case of cohesive particles, as well as a ridge of high (adjacent to the jet) to low (near the vessel walls) voidage representing “dead zones” of fluidization.

As an alternative to scanning transmission tomography, Positron Emission Tomography has also been applied successfully in the investigation of flow characteristics in multiphase granular systems by monitoring the trajectories of single radio-labelled particles as they move in the system. A positron camera used to detect coincident photons coming out in opposite directions after a positron annihilation has been constructed by Hawkesworth et al. (1986)\(^ {18}\). A spatial resolution of 6–8 mm (full width at half maximum) is achieved in tracking a single particle of similar dimension, while the motion of the particle is monitored by taking a number of exposures over a short time period. Two statistical methods, one based on a conventional backprojection of the photon trajectories, the other based on the unprojected trajectories, have been developed to determine particle position.

The feasibility of the new technique for particle tracking was tested on a model fluidized bed by Bemrose et al. (1988)\(^ {2}\). The method for particle tracking by using the photon trajectories has been improved in a recent work by Parker et al. (1993)\(^ {15}\). The spatial resolution in Positron Emission Particle Tracking (PEPT) is referred to in terms of the uncertainty error in the estimation of the particle location (3-D standard deviation), and depends upon the number of events used for determination of the particular location. The temporal resolution meets very high standards as each exposure is logged-in within a time period at the order of milliseconds. The new algorithm rejects corrupted events due to scattering or invalid coincidences, and always keeps an optimum set of events for tracking the particle according to its velocity. The new method encourages the use of smaller tracers (2 mm diameter) instead of the bigger ones used until now due to the limited resolution of the PET images. PEPT has also been applied recently to powder mixing studies, providing a way to calculate the particle density at each point as a function of the filling level and the shaft angle (Beynon et al., 1993)\(^ {3}\).

Non-ionizing methods such as electrical impedance and NMR are also in current use in the study of granular systems. Electrical imaging has found wide application in multiphase systems and especially in fluidized beds. Recent work in fluidized beds revealed useful information concerning global voidage distribution within the bed (Halow and Nicoletti, 1992)\(^ {5}\), Halow et al. (1993)\(^ {7}\). There are also some limitations in these electrical methods such as poor resolution, blurring due to averaged permittivity for each pixel, and non-linear effects due to the electrical interactions between particles which distort the proportionality of void fraction to measured permittivity.

Nuclear Magnetic Resonance imaging has been widely used in flow studies of multiphase systems in both the medical and industrial areas. Based on the excitation and relaxation of the magnetization of a medium, it provides images with high spatial resolution. The choice of solids to be used in an NMR study must be very strict since the NMR signal from dry solids has very short relaxation times, while the solids moisture content improves the detection accuracy significantly. Furthermore, the NMR technique is restricted in terms of hardware cost and implementation to the study of reasonably small objects thus being inappropriate for large-scale industrial applications. A recent work of NMR measurements from a rotating silo of packed particles has been reported revealing a shear and a rigid body motion region (Nakagawa et al. (1993)\(^ {13}\).

In addition to the work highlighted above, a novel tomographic facility is presently under development at Surrey which is dedicated to the investigation of 3-D granular systems. A single gamma-ray source providing a fan beam and facing an array of detectors will for the first time provide measurements of voidage profiles accurate to a spatial resolution of less than 1 mm over scan times at least four times shorter...
(i.e., in seconds rather than minutes of flow) than those available with the existing parallel beam scanner configuration (Hosseini-Ashrafi and Tüzün (1993)\textsuperscript{9}). Furthermore, a dual photon technique applied for the analysis of the raw data will enable the quantification and characterization of flow of particulate systems consisting of more than one solid phase. Various particles of a size comparable to the acquired spatial resolution will play the role of tracers following the flow of the system in order to facilitate the extraction of simultaneous velocity profiles and voidage patterns in 3-D flow vessels. The details of the experimental work in progress with different systems are described below. The bulk of the work to date at Surrey has been conducted using a multiple source parallel beam scanner whose details are given in sections 2 and 3, while the details of the most recent fan beam scanner project are presented in Section 4.

2. Investigation of air/solid systems using a parallel beam scanner

The CAT scanner used in these experiments employs a scanner head consisting of six 153Gd sources emitting gamma photons at energies of 44 keV and 100 keV, and six collimated CsI scintillation detectors arranged in a parallel geometry. 153Gd has a half life of 241 days and high specific activity which provides high photon fluxes with the minimum source size. Each scan is taken by translating the head laterally in small steps in order to sample the object properly, and then rotating by 1.5° to make another translation. The scan finishes after completing a rotation of 180°. The collimators used in these experiments had 1mm and 2mm aperture width, which actually governs to a large extent the final image resolution. The vertical resolution (length of the aperture) was 3 mm, allowing good precision in our measurements. The fastest total scan time achieved was 90 sec with the 2 mm collimator. A 2 m tall Perspex cylinder of 96mm inside diameter is mounted on a conical hopper section of 10° half-angle and a 10 mm diameter orifice. The hopper is allowed to move vertically with different velocities and in different steps. A schematic diagram of the experimental rig is shown in Fig. 1.

Polymethyl methacrylate spheres of size distribution 90-1000 μm were used to prepare mono-sized and binary beds in different proportions and size ratios. The experimental work involved consecutive scans at different heights of beds with flow history during a series of start-stop experiments to achieve better image reconstruction quality, and also of static beds with no flow history. Fig. 2 compares images of a mono-sized and a binary mixture in a static condition. The boundaries of the particles cannot be distinguished since the spatial resolution of the scans is higher than the individual particle size, and the solid fraction content at every pixel cannot be calculated by direct observation methods.

Therefore an analytical procedure has been developed according to the following equation

$$\eta(x,y) = \frac{\mu(x,y) - \mu_{\text{air}}}{\mu_{\text{solid}} - \mu_{\text{air}}} = 1 - E(x,y)$$

where $\mu(x,y)$ represents the reconstructed linear attenuation coefficient value of the pixel with the unknown solids content, and $\mu_{\text{air}}$ and $\mu_{\text{solid}}$ are the reconstructed values for air and solid-filled pixels, respectively. These values are actually averaged over

![Fig. 1](image-url)
Fig. 2  Reconstructed images of the same horizontal plane across two different static beds:
(A) mono-sized bed of spherical particles, diameter 850-1000μm, no flow history, static imaging
(B) binary mixture bed of 850-1000μm and 90 - 125μm spherical particles, 30% by weight fines, no flow history, static imaging

Fig. 3  Cross-sectional profiles of flowing voidage in axially symmetric flow: (a) line scan data for a binary bed of 75\% b.w. of 850-1000μm and 25\% b.w. of 125-212μm diameter spheres after 5s of discharge at height Z=230mm; (b) polar scan data for the binary mixture bed as in (a) but after 60s of discharge and at Z=400mm; (c) annular segment scan data for a mono-sized bed of 125-212μm diameter spheres after 7s of discharge and at Z=140mm (LAVF = line averaged void fraction and AAVF = annular averaged void fraction). Line scan data are averaged across L-R axis and plotted along T-G axis.
a sample of pixels of the image containing only air or solid. The above procedure was tested against phantoms of known solid content at every point with an accuracy of ±1.5%. The void fractions are calculated along each line (L-R) according to Eq. (1), and the mean values (PMVF) are plotted along line (T-R) as can be seen in Fig. 3. The possible axial symmetry of flow and the radial distribution of the density function is investigated by transferring the linear profiles of interstitial voidage to Cartesian and polar coordinates as can also be seen in Fig. 3. The Cartesian coordinate system keeps the pixel geometry of the image, whereas in the polar coordinate system, averaged values of voidage are calculated along a preselected radius and plotted against various angles $b$. Furthermore, interstitial voidage can be presented as averaged values within equal-area strips spanning radially away from the centre of the hopper. The averaging procedure within an annulus of thickness comparable with some tens of particle diameters causes a smoothing effect on the voidage fluctuations, as can be clearly seen in Fig. 3 where voidage profiles on the other coordinate systems are presented as well.

Static profiles of mean voidage values with height for a mono-sized and a binary mixture is demonstrated in Fig. 4. There is no significant alteration of the mean void fraction with height in both the cylindrical and the conical section of the hopper, but there is a visible increase in going from the conical to the cylindrical section. A well-defined maximum propagating with time up the silo is demonstrated in Fig. 5 where the flowing profiles with height of a mono-sized and a binary mixture are presented. A minimum value of voidage can be clearly detected within the cylindrical section close to the transition line.

Faster scan times of the order of 20 sec have been achieved by using a new quantitative technique employing single profile measurements across a bed of mono-sized and binary mixtures and a consecutive radial transformation of the linear data according to the equation

$$ F(r) = -\frac{(1/\pi)^{1/2}}{R} \int_{r}^{R} \frac{F(x)dx}{(x^2-r^2)} \quad (2) $$

where $F(r)$ is the radial density function and $F(x)$ is the line integral as can be seen in Fig. 6. The technique was tested successfully by using a specially constructed phantom presented in Fig. 7. A monosized bed consisting of polymethyl methacrylate powder in the 125-200 μm size range and a binary mixture of 80% by weight of acrylic beads in the 0.85-1.0 μm size range with 20% by weight of fines were scanned during discharge using the new absorptiometric method; the radially transformed data at different heights are presented in Fig. 8. The collimator aperture dimensions are 2 x 3 mm, providing a resolution of 2 mm across the hopper and a precision of better than 1%. The significant time variation of voidage in the case of the mono-sized bed of fine particles indicates the presence of air-impeded flow, whereas in the case of the binary mixture, the time variation of voidage is quite small and a dilated region in the centre of the hopper is evident. The spatial resolution of these scans is 2 mm, which is of the order of 2-10 particle diameters. Therefore, they will not allow the detection of the "empty annulus" at the orifice plane which is known to have a width of about 1-2 particle diameters (Arteaga and Tuzun (1990)). The spatial variation of voidage with height is significant over a height of 50 mm above the orifice (5 or so orifice diameters) in the case of the binary mixture, whereas at greater heights the profiles are reasonably flat. A significantly dilated region in the case of the mono-sized mixture is predominant over a height of 50 mm from the orifice with a similar shape profile as in the binary case for greater heights.
Fig. 5  (a) Vertical profiles of the plane mean voidage in the model silo during batch discharge of a binary mixture bed of 75% b.w. of 850-1000μm and 25% b.w. of 125-212μm diameter spheres (PMVF = plane mean void fraction); (b) Vertical profiles of the plane mean voidage in the model silo during batch discharge of a mono-sized bed of 125-212μm diameter spheres (PMVF = plane mean void fraction).

Fig. 6  Coordinate system used in the definition of the transformation coordinates.

Fig. 7  (a) Schematic diagram of the axially symmetric Perspex phantom; (b) Experimental values of F(x) across the axially symmetric phantom of (a). (c) Calculated F(r) values for the axially symmetric phantom of (a).
3. Determination of radial voidage profiles in coarse granular solid/liquid mixtures

The encouraging results from the use of single profile photon absorptiometry in air-based systems provided us with the opportunity to investigate the interstitial voidage of the nearly buoyant, coarsely granular solid and liquid mixtures encountered often in food processing applications. Single profiles were taken across the hopper by scanning in 1mm steps over a time period of 5-10 sec. The experimental apparatus is shown in Fig. 9. A 2.17 m tall Perspex cylinder of 144 mm inside diameter is mounted on a conical hopper section of 30° half-angle and a 34 mm diameter orifice. The outlet of the conical section is connected to a stand pipe 34 mm in diameter used for retaining water control of the flow by preventing air from entering the system. The flow is controlled by a water column which is kept to a certain level by a main water supply connected at the top of the hopper. A small amount of potassium iodide (2% by weight to avoid particle floating) is added to the water as a contrast agent to improve the precision in the measurements, since the attenuation coefficients of pure water and the nearly buoyant particles are very close to each other. A very small amount of a dye is added as well to monitor the penetration of the water column to the actual solid-liquid contact.
Extruded plastic beads 3.76 mm in diameter are used to prepare a solid-liquid bed consisting of 60% by weight solid and 40% by weight water. The scanner is operated in the dynamic mode where the hopper travels vertically with different velocities and in various steps, and consecutive scans are taken at various heights. The scans were taken at heights of 34 mm above the orifice, at the orifice itself, and 10, 34, and 170 mm below the orifice as shown in Fig. 9. The solid fraction is calculated according to the equation

\[ \eta = K \frac{F_s - F_c}{F_s - F_w} \]  

(3)

where \( F_s \), \( F_c \), and \( F_w \) are the measured raysums from the solution of water and potassium iodide only, the liquid-solid bed, and the hopper walls, respectively. The constant \( K \) is calculated from a calibration procedure applied to a packed bed prepared with a known solid fraction (0.71), and is found to have a value of about 5 for the particular plastic beads.

A whole tomographic image of the aforementioned solid-liquid mixture at the height of 170 mm below the orifice level is presented in Fig. 10. The boundaries of the individual particles can now be clearly distinguished since the particle size is larger than the collimator aperture, which in this case is 1 mm. The information obtained with the complete scan is actually three-dimensional, but the longer scan time necessary for a complete tomograph in contrast with the potential of the new single profile technique to provide fast information along any object diameter makes the latter more preferable. Fig. 11 shows the line profiles obtained at the same height over two consecutive 2-minute scan periods under constant mass discharge rate condition. As seen in Fig. 11, the reproducibility of the scan data is accurate to within 1-2%.

The linear profiles together with their radial transforms are presented in Figs. 12-16, and the spatial variation of solid fraction with height is presented in Fig. 17. These results give the best evidence for the symmetry of the profiles and the dilation of the bed during discharge. Another interesting feature is the smoothing effect that the radial transformation has on the linear profiles due to averaging within reasonably thick annular regions. It is also worth noting here that when the collimator aperture size is much smaller than the particle size being imaged, the fluctuation of the pixel-to-pixel value of the solids fraction becomes quite considerable. This is due to the large solid objects aligning themselves in front of a much narrower beam. To exclude this effect, it is necessary to choose a collimator aperture size larger than the particle size, which in this case requires at least a 5mm resolution.

As seen in Fig. 17, the variation of solid fraction with height appears to obey a similar pattern with both the linear and the radial data. However, it is
Fig. 12 (a) Linear profiles at 34mm above the orifice of a bed of 60% b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide in static condition and under constant mass discharge lasting 4.2 min. (b) Radially transformed profiles from (a).

Fig. 13 (a) Linear profiles at the orifice of a bed of 60% b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide in static condition and under constant mass discharge lasting 4.2 min. (b) Radially transformed profiles from (a).

Fig. 14 (a) Linear profiles at 10mm below the orifice of a bed of b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide in static condition and under constant mass discharge lasting 2.1 min. (b) Radially transformed profiles from (a).
Fig. 15 (a) Linear profiles at 34mm below the orifice of a bed of 60% b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide in static condition and under constant mass discharge lasting 2.1 min. (b) Radially transformed profiles from (a).

Fig. 16 (a) Linear profiles at 170mm below the orifice of a bed of 60% b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide in static condition and under constant mass discharge lasting 2.1 min. (b) Radially transformed profiles from (a).

Fig. 17 (a) Vertical profiles of the linear mean solid fraction (LMSF) in static condition and under constant mass discharge of a bed of 60% b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide. (b) Vertical profiles of the radial mean solid fraction (RMSF) in static condition and under constant mass discharge of a bed of 60% b.w. extruded plastic particles 3.76mm in diameter and 40% b.w. solution of water and potassium iodide.
worthwhile noting here that particles are moving faster than the surrounding liquid which results in noticeable voidage and pore-pressure gradient across the orifice. Further work is currently underway to quantify the sudden changes in voidage immediately above and below the orifice plane more accurately, in order to relate these voidage gradients to the measured pore-pressure gradients across the hopper orifice.

4. A novel fan beam scanner for simultaneous measurement of voidage and particle velocities

The new tomographic scanner is to be used as an inspection tool to simultaneously characterize the velocity field and voidage structure in 3-D granular flows with competitive spatial and temporal resolutions.

The new scanner presented in Fig. 18 employs eighteen collimated CsI detectors arranged in a fan geometry facing a single source of $^{153}$Gd of 1 Ci (37 GBq) activity. The collimation consists of tungsten alloy blocks attached one to the other with a collimator aperture width of 2 mm and 5 mm in length, which permits good statistics and at the same time a spatial resolution that can be better than 1 mm. The scanner moves over $180^\circ$ completing 110 projections where each detector completes an eight-step move in every projection, thus infilling the empty space between the detectors according to the Nyquist criterion for sampling. Therefore, 110 projections with 144 raysums
projection contribute to the reconstruction of an array (144 × 144) of attenuation coefficient values.

The convolution backprojection algorithm is used for the reconstruction after the fan beam data set has been transformed to the equivalent parallel one using a simple geometric transformation.

A range of object diameters (5-20 mm) can be fitted into the fan beam at various distances from the source, allowing scanning at various parts of an object such as the conical and the cylindrical section of a hopper. The spatial resolution of the new scanner can reach values of less than 1mm, whereby the timing resolution can be 4-5 times less than that of the parallel beam scanner used until now in granular flow experiments (i.e. best performance: less than 1min).

The timing resolution can be improved by applying incomplete projection tomography where the scanning is focused either at a certain region of the vessel cross-section (Region of Interest Tomography) (Gentle and Spyrou (1990)4) by incomplete linear sampling, or at a minimum number of symmetric positions around the object (Limited Angle of View Tomography) (Nalcioglou et al. (1983)14) Specially developed algorithms will reconstruct the image by either interpolating or extrapolating the missing data. It is hoped that once this novel software is in place, it will be possible to obtain complete tomographic scans in a few seconds.

To track individual particles within the flow field, scanning is performed at two energy levels, allowing the concentrations of two different components together with the voidage distribution (third phase) to be determined simultaneously in a single experiment. Consecutive cross-sectional scans taken at different times along the vessel containing the tracer particles can be used to create a volume reconstruction of the system, which will in turn allow a three-dimensional determination of the velocity field as can be seen in Fig. 19.

In radiation tomography, the attenuation coefficient depends on the energy, the atomic number of a material with elemental constitution, and on the electron density at a particular position. Therefore, for a system with two components of different atomic numbers, the determination of their respective solid concentration is performed by using two photon beams with different energy peaks well separated from each other. If a third phase is present in the system, the determination of the solid concentration becomes difficult unless the third phase distribution is constant throughout the system. But this is not true for three-phase granular systems in the flow regime where the concentration varies randomly in any position. Therefore, a third equation expressing an a priori information about the object becomes necessary. Unlike the medical applications (Goodwin (1987)5), the granular flow experiments are run under constant total volume conditions which provide the third necessary equation thus resulting in

\[ \mu_{\text{low}} = c_A \mu_{A}^{\text{low}} + c_B \mu_{B}^{\text{low}} + c_C \mu_{C}^{\text{low}} \]

\[ \mu_{\text{high}} = c_A \mu_{A}^{\text{high}} + c_B \mu_{B}^{\text{high}} + c_C \mu_{C}^{\text{high}} \]

\[ c_A + c_B + c_C = 1 \]

where \( c_A, c_B, c_C \) are the volume fractions of each component having attenuation coefficients of \( \mu_A, \mu_B, \mu_C \), respectively, and \( \mu_{\text{low}}, \mu_{\text{high}} \) are the reconstructed mean attenuation coefficients for the two energies at a particular pixel where all three phases are present.

The selection of the materials to be used for the dual photon measurements of a two-phase solid mixture in air or liquid is based on the minimum detectable fraction (MDF) (Kouris et al. (1982)11) of each solid component when it is embedded in a matrix consisting of the other solid component and the air or liquid. As shown in Fig. 20, for a water-based system, a difference of at least 10% of the attenuation coefficients between the two solid components is the
optimum threshold for the selection of the materials to be used in flow experiments, as in this region, the limits of detection for both components appear to have reasonable separation for attenuation changes of the order of 0.1 % (e.g. glass Pyrex with either silicon or polyvinyl chloride embedded in water will meet this criterion). It is expected that experiments will also be possible using agricultural and food materials as well as industrial ceramic and plastic powders.

5. Conclusions

A tomographic and an absorptiometric technique are demonstrated here as two powerful non-invasive tools to investigate the interstitial voidage in axially-symmetric particulate flows both in air and in liquids. The application of these methods to granular flow experiments, and especially to the solid-liquid systems, is believed to be the first of its kind in the particle technology field. Since both the spatial and the temporal resolutions reach a high level of compensation, providing highly reproducible dynamic data, very useful results related to the spatial and temporal variation of the interstitial voidage structure for flowing density powder are achieved. The particle tracking technique based on the dual photon transmission principle should soon allow us to couple these dynamic voidage maps with solids velocity fields, thus opening the way for new theoretical developments in the study of granular flows.

Nomenclature

| Symbol | Description |
|--------|-------------|
| CA, CB, CC | Volume fractions of a three-phase mixture |
| Do | Orifice diameter |
| F(r) | Radial density function |
| F(x) | Line integral function |
| Fs | Measured raysum from water-potassium iodide solution |
| Fc | Measured raysum from solid-liquid bed |
| Fw | Measured raysum from hopper walls |
| K | Constant |
| R | Object radius [m] |
| z | Height above the outlet [m] |

Greek letters

| Symbol | Description |
|--------|-------------|
| ε(x,y) | Void fraction |
| η(x,y) | Solid fraction |
| μair, μsolid | Linear attenuation coefficients of a pixel filled with air or solid only [m⁻¹] |
| μm(x,y) | Mean linear attenuation coefficient of a mixture [m⁻¹] |
| μhigh, μlow | Linear attenuation coefficients at two different energy levels [m⁻¹] |
| μA, μB, μC | Linear attenuation coefficients of three components of a mixture [m⁻¹] |

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Dr. Nicholas M. Spyrou obtained his first degree in Mechanical Engineering with Nuclear Engineering and joined Imperial College, University of London to do postgraduate work in reactor physics leading to a Master’s degree. He was subsequently employed there as a research assistant for doctoral research in neutron cross-section measurements. Since 1969 he has been at the University of Surrey using radiation physics in biomedical, environmental and industrial applications. His main fields of research are in imaging and in trace element analysis using nuclear probes, for which he was awarded an honorary doctor of medicine degree in 1987. He has been Chairman of Medical Physics since 1978 and is Reader in the Department of Physics. He has supervised successfully over 40 PhD students and is the author of more than 150 papers.