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Computer Assisted Gamma and X-Ray Tomography: Applications to Multiphase Flow Systems

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Abstract

The application of X-ray and gamma ray transmission tomography to the study of process engineering systems is reviewed. The fundamental principles of tomography, the algorithms for image reconstruction, the measurement method and the possible sources of error are discussed in detail. A case study highlights the methodology involved in designing a scanning system for the study of a given process unit, e.g., reactor, separations column etc. Results obtained in the authors' laboratory for the gas holdup distribution in bubble columns are also presented. Recommendations are made for the Advanced Fuels Development Unit (AFDU) in LaPorte, TX.

Executive Summary

In process vessels, involving two or three phases it is often important not only to know the volume fraction (holdup) of each phase but also the spatial distribution of such holdups. This information is needed in control, trouble shooting and assessment of flow patterns and can be observed noninvasively by the application of Computed Tomography (CT). This report presents a complete overview of X-ray and gamma ray transmission tomography principles, equipment design to specific tasks and application in process industry.

The measurement principle used in gamma ray tomography, based on attenuation of a collimated beam of radiation, is common to densitometry which is frequently employed in the industry for obtaining chordal average phase holdups in multiphase reactors and other process units. The important differences and advantages of CT compared to densitometry are highlighted. The available scanning modes, i. e. strategies for acquiring data for CT are reviewed from the perspective of industrial process units and reactors. All the important elements of the hardware required in the implementation of a CT scanner are discussed. A variety of algorithms for image reconstruction are compared on the basis of results for simulated and physical phantoms (test cases). The superiority of the Estimation-Maximization (EM) algorithm is established.

The measures of CT scanner performance are discussed in terms of the achievable spatial temporal and density resolution. Various possible errors in the measurement and image reconstruction process are outlined, as well as the means for alleviating these errors. The mechanics involved in the CT scanner design is illustrated by discussing the design of the system built at the Chemical Reaction Engineering Laboratory (CREL) at Washington University in St. Louis and the system that was implemented at the Nuclear Engineering Department at Ohio State University (OSU). In the first case the spatial resolution was of importance, in the other case temporal resolution was of prime consideration. Compromises that need to be made to achieve a given design specification are discussed.

The literature on the use of tomography for studies of fluid dynamics in a variety of systems is summarized. The results for the gas holdup distribution in a bubble column obtained at CREL are discussed. Finally, a design for a CT scanner that can be implemented on a large scale industrial reactor is provided. The advantages of implementing this system include the availability of data on gas holdup distribution in greater detail in comparison to what is obtainable by gamma densitometry that is currently being used at LaPorte on the AFDU reactor. This experimental information is essential to verify phenomenological and computational fluid dynamic models as well as scale-up rules used in reactor design. This indeed is the purpose for which the CT scanner at CREL is used. It is hoped that this report will encourage a more wide spread use of CT technology in R & D and industrial practice.

1 Introduction

Equipment design for the process industry requires proper understanding of the fluid dynamics which in turn often relies on experimental investigation of three dimensional and frequently multiphase flow fields. The parameters of interest are velocity, phase and or species concentration and temperature distribution throughout the flow field. Although traditional measuring methods based on the use of probes have the ability to provide accurate measurements with fine time resolution, such probes are not only intrusive but they also need to be moved through the volume of the system being studied in order to map the entire flow field. Methods that have the ability to provide the relevant measurements throughout the flow field without disturbing the flow are clearly advantageous. Computed Tomography (CT) is one such technique that is capable of providing the concentration, or the holdup distribution, of the phases in multiphase systems. The advantage of tomography lies in its noninvasiveness and in the ability to obtain the parameters of interest over an entire cross section of the flow field of interest. If several such individual layers, each with their measured distribution are stacked up, a three dimensional field can be reconstructed. The void fraction, and its distribution, in a two phase flow system are important in determining the interfacial area available for heat and mass transfer between the phases. The characterization of inhomogeneous two phase flow fields is complete only when the holdup and its distribution are also measured in addition to other hydrodynamic quantities such as phase velocity.

Tomography has been in use in the medical field for diagnostic radiology for more than 50 years. However, the application of tomography to engineering applications is relatively recent (mid-1980's). Applications range from nondestructive testing of manufactured components (Del Grande et al., 1993, Martz et al., 1993), the investigation of process equipment (process tomography) (Dickin et al., 1993), to underground imaging in relation to environmental remediation of contaminated soil and groundwater (Daily and Ramirez, 1995). In the process industry, tomography aids in the characterization of the flow in chemical reactors, which is essential in providing an accurate basis for modeling of the reaction processes involved. In these systems, the phases (especially a solid phase) involved are opaque and prevent the use of optical techniques for the measurement of flow parameters. Thus, tomography in its various forms provides the only means to obtain the required information.

Although in the medical field tomography is largely based on the use of high energy electromagnetic radiation such as X-rays and gamma rays, for engineering applications a number of other forms of tomography have evolved. These include tomography based on the use of ultrasound, impedance (capacitance), and even visible light. The methods based on the use of gamma rays can be classified into emission and transmission tomography. In emission tomography the geometric distribution of the activity of radionuclides introduced

into the system is imaged. One encounters positron emission tomography and single photon emission tomography depending upon the kind of radiation used. Both are extensively used in medical imaging. Transmission tomography, on the other hand, is based on the principle of measuring the attenuation of a beam of radiation transmitted through the object. Based on a number of such attenuation measurements along several paths through the object, an image of the absorption coefficients within the scanned section is reconstructed. Phase holdup and its distribution can be derived from the absorption coefficient distribution for a two phase flow system, since the absorption coefficients are a function of the type of material traversed by the beam of radiation. In ultrasonic tomography, the gas bubbles are considered to be opaque plates that absorb sound. The large difference in the ultrasonic impedance between a gas and a liquid phase serves as a means for discriminating between the phases. Impedance tomography is based on measuring the electrical resistance, or the dielectric permittivity, in the flow between pairs of electrodes, a number of which are evenly spaced around the test section. Although both ultrasonic and impedance tomography have the advantage of being capable of fine temporal resolution, the achievable spatial resolution is rather coarse owing to the measurements being affected by the holdup distribution as well as by a number of other parameters such as the electrical properties and temperature of the medium. X-ray and gamma ray tomography on the other hand are capable of high spatial resolution but temporal resolution is limited by the activity of the source used. Use of a higher activity source, or a X-ray tube with a higher power output, is constrained by radiation safety considerations. Thus, most often, with these systems the measurements of the concentration or holdup that is obtained is time averaged.

The focus of this report is on gamma and X-ray transmission tomography. We begin by first discussing the basic principles of tomography. The different hardware configurations for arranging the radiation detectors and the source of radiation, as well as the methods for measuring the attenuation are described. The various mathematical methods used for reconstruction of the density distribution from the attenuation measurements as well as a comparison between the various methods are then presented. Finally, the application of computed tomography for the experimental investigation of multiphase systems is illustrated through a few examples and some possible industrial and process applications are outlined. In presenting the above material we highlight our own experience in implementing a tomographic system for holdup measurements in two phase flow systems such as bubble columns and fluidized beds.

2 Technical Aspects of Computed Tomography

2.1 Basic Principle

A narrow beam of radiation traversing a straight path through an object gets attenuated primarily by absorption and to a lesser extent by scattering. If the object were to be divided into a number of elements, then the problem in CT is to determine the extent to which the material in each element attenuates the beam, and to display this information in the form of an image.

The intensity of a beam of monoenergetic radiation that is transmitted through a homogeneous material is governed by the Beer-Lambert's law which can be expressed as:

$$T = \frac{I}{I_0} = e^{-\mu \rho l} \quad (1)$$

where T is the transmission ratio, I_0 the incident radiation, I the detected radiation, μ the mass attenuation coefficient, ρ the medium density, and l the path length through the medium. The product $\mu \rho$ is defined as the linear attenuation coefficient of the medium and is the ratio of the percentage change in the flux of the beam to the change in distance as the beam traverses the medium (Newton and Potts, 1981). The product $\mu \rho l$ is referred to as the absorptance of the medium. If the medium is made of two materials of mass attenuation coefficients μ_1 and μ_2 , densities ρ_1 and ρ_2 , and thickness l_1 and l_2 , respectively, the net absorptance, A , is:

$$A = \rho_1 \mu_1 l_1 + \rho_2 \mu_2 l_2 \quad (2)$$

If $l_1 = \epsilon_1 L$ and $l_2 = (1 - \epsilon_1) L$, where $L = l_1 + l_2$, then:

$$A = [\rho_1 \mu_1 \epsilon_1 + \rho_2 \mu_2 (1 - \epsilon_1)] L \quad (3)$$

where ϵ_1 is the void fraction of one of the phases.

The measured quantity $\ln I_0/I$ is the net absorptance and is the integral sum of the attenuation coefficients of the material along the incident line. A single measurement of the attenuation can be used to compute ϵ_1 , the fraction of the medium along the beam path that is occupied by material one. The information obtained is global (averaged along the path), and no information can be obtained regarding the composition of the medium locally. Since the attenuations along a beam path vary considerably, a large number of such attenuation measurements of the object must be obtained from many directions to determine the attenuation coefficient of each element (for a two dimensional slice of the object the element is called a pixel). This measurement followed by a mathematical procedure

for computing the attenuation coefficients of the pixels constitutes the basic idea behind tomography. Since the reconstruction process is performed by using a computer, and since the process of data collection is automated by interfacing the hardware to a computer, the process is popularly referred to either as Computer Assisted Tomography (CAT) or as Computed Tomography (CT).

2.2 CT Scanning Modes

Scanners for transmission tomography have some source of radiation, such as an X-ray tube or an encapsulated gamma ray source, positioned on one side of the object to be scanned and a detector or a set of detectors arranged on the other side. Transmission measurements of a collimated beam of radiation are obtained along several paths from many directions around the object to cover the cross section as uniformly as possible. The term 'CT scanning modes' refers to the geometrical arrangement of the combination of the detectors (or detector) and the source of radiation, and the method adopted for acquiring the data for the requisite number of projections. In principle, it involves rotating the source-detector arrangement synchronously with respect to the test section.

There are three methods of scanning that are commonly used. The simplest of these is parallel scanning in which a source, emitting a single pencil beam of radiation, and a detector are coupled together so that the detector is always facing the source as illustrated in Fig. 1(a). For obtaining a single view, the source and detector move on opposite sides of the test section measuring the absorptance (also called attenuation) at each position i. e. along the chord that connects the detector and the source. For the next view, the detector source arrangement rotates about the test section and the translation is repeated. This method of scanning is very time consuming. The other two methods result in rapid collection of the data. The second method has an array of detectors facing a single source. The source is collimated in such a way that the pattern of the beam is a fan with a thickness of about 5 to 10 mm (Fig. 1(b)). A single view is obtained for a given position of the source-detector arrangement, which is then rotated to get the next view. Another method, referred to as the fourth generation scanning configuration, is the fixed detector-rotating source arrangement in which a large number of detectors are mounted on a fixed ring as shown in Fig. 1(c). Inside this ring a fan beam source rotates around the test section, and the outputs of the detectors facing the source are sampled every few milliseconds. All such samples for any one detector are referred to as a detector-vortex fan and constitute one view of the object.

Figure 1: CT scanning modes, (a) Parallel beam scanning mode, (b) Rotating fan beam scanning mode, (c) Fixed detector-rotating source scanning mode.

2.3 Image Reconstruction from Projections

Given a set of projections (ray sums), the next step is to reconstruct the attenuation coefficient distribution (image). Equation (3) for the absorptance can be written in a more general form as:

$$P(l, \theta) = \int_L f(x, y) ds \quad (4)$$

where $P(l, \theta)$ called the projection is the integral of the attenuation coefficients along the path L , $f(x, y)$ represents the image function and L indicates the line over which the integral is obtained. The basic problem then is, the inversion of an integral equation along a linear path through a scalar field. Radon (1917) showed that a function with finite support, continuous and having continuous first derivatives, can be uniquely reconstructed from an infinite set of line integrals in the form of Eq. (4). The solution, known as the Radon transform, is given by:

$$f(x, y) = \frac{1}{4\pi^2} \int_0^{2\pi} \int_{-\infty}^{\infty} \frac{-1}{l - x \cos \theta - y \sin \theta} \frac{\partial P(l, \theta)}{\partial l} dl d\theta \quad (5)$$

where $(l - x \cos \theta - y \sin \theta)$ is the perpendicular distance of the point (x, y) from the line l , and $P(l, \theta)$ is the integral of $f(x, y)$ along line l (ref. Fig. 2). Utilization of the Radon transform for image reconstruction is possible only in theory since it calls for an infinite number of noiseless projection measurements. In practice, methods that approximate the Radon's transform in some sense are used. Many different types of algorithms are available for the reconstruction process and the principle behind the important ones are briefly presented in what follows.

The integral transformation method of reconstruction is based on approximating the inverse Radon transform. The essential steps in obtaining the inverse Radon transform of a function of two variables are :

1. Partial differentiation of the function with respect to its first variable to obtain another function q .
2. q is Hilbert transformed with respect to its first variable to obtain a function t . Thus if q is a function of two variables, l and θ , for any real number pair (l', θ) , the Hilbert transform is defined as :

$$[Hq](l', \theta) = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{q(l, \theta)}{l' - l} dl$$

The improper integral needs to be evaluated in the Cauchy principle value sense.

3. t is then backprojected onto the original function domain. Given a function t of two variables, its backprojected function $[Bt]$ is a function of two polar variables defined

Figure 2: Geometry for Image Reconstruction.

as :

$$[Bt](r, \phi) = \int_0^\pi t(r \cos(\theta - \phi), \theta) d\theta$$

The back projection operation can be described with reference to Fig. 2. If $P(l, \theta)$, the projection at a given angle θ , is represented as $g_\theta(l)$, then for different distances l from the center, g_θ is a set of projections (line integrals) taken in the θ direction. If the values of $g_\theta(l)$ are backprojected or smeared back over the domain, the resulting function, $b_\theta(x, y)$, at each angle, is given by :

$$b_\theta(x, y) = \int g_\theta(l) \delta(x \cos \theta + y \sin \theta - l) dl$$

Thus, in the backprojection operation each projection at a point t (Ref. Fig. 2) makes the same contribution to all the pixels along the line l . The complete backprojected function is the sum of all such functions corresponding to all the angles. Hence, the

Figure 3: Pictorial representation of the Fourier slice theorem

approximation $f'(x, y)$ to $f(x, y)$ is :

$$\begin{aligned} f'(x, y) &= \int_0^\pi b_\theta(x, y) d\theta \\ &= \int_0^\pi \int g_\theta(l) \delta(x \cos \theta + y \sin \theta - l) dl \end{aligned} \quad (6)$$

4. The value of $f'(x, y)$ is then normalized by multiplying it by $-1/(2\pi)$.

A very commonly used algorithm for reconstruction in commercial CT scanners is the filtered backprojection, or its equivalent, the convolution backprojection system. The implementation of these algorithms on a computer gets simplified by making use of Fast Fourier Transforms (FFT). With the use of FFT the execution of the algorithm is also faster. The principle basis for these algorithms is the central section theorem (Gordon and Herman, 1974) which states that all the ray sums or the projections in one view of the object constitute the two dimensional sinusoidal components of the unknown image at that angle. Thus, the measured projections at each angle are used to derive the Fourier Transform (FT) of the object at that angle. This, as shown in Fig. 3, constitutes a line in the Fourier plane at the same angle. Repeating this for all the projections then provides the FT of the image of the section being scanned in the form of a series of lines radiating from the center. The reconstruction is then finally obtained by taking the inverse Fourier transform.

Before the inverse FT is computed, the FT in the plane is first multiplied by a band-limited filter function. The purpose of this filtering is to reduce the blurring caused by the

Figure 4: Modification of the image of a point object by a filter function

back-projection process. As the backprojection process leads to a uniform assignment of the projected value along the beam path, the reconstruction of a point object appears as an array of lines or spokes intersecting at the point being reconstructed and therefore the image is not sharp. Since an image is a collection of points, the blurring of the image is a result of the backprojection process. In order to reduce the effects of blurring it is necessary to suitably modify the projections before they are backprojected. Each point is therefore replaced by a modified function as shown in Fig. 4. The modified function has the same amplitude as the point object but includes negative extensions on either side of its position that will cancel out the blurring effect of the backprojection process. The modified function for each point of the image has the same shape but with an amplitude that is a function of the amplitude of the original point. Summation of the modified functions leads to addition and subtraction of the negative and positive parts of the functions leading to the convolved projections. All this is effectively achieved by the multiplication of the FT of the filter function with the FT of the projections in Fourier space. In order to compute the inverse FT of the filtered projections it is also necessary to interpolate the FT of the filtered projections that are known along a finite number of radial lines from a polar grid on to a cartesian grid. Traditionally, either a nearest neighbor or a linear interpolation approach is used. This generally leads to large errors as the radial points get sparser with increase in distance from the center. The end result, caused by this interpolation, is that the high frequency components of the image are in greater error leading to image degradation.

The above description of the reconstruction process holds for the projections measured in

the parallel beam scanning mode. For image reconstruction from the measurements obtained with fan-beam scanning configuration, the general idea provided above is still applicable, but the details of the algorithm derivation differ. The differences arise mainly because of the different mathematical expressions that arise in the algorithm derivation process. Consequently, the filter used is different, and instead of a simple backprojection, as used for parallel beams, it is necessary to implement a weighted backprojection. Details of the algorithm as well as the implementation on a computer can be found in Herman et al. (1976). Another approach that is used for reconstructing fan beam projections is to first convert the fan-beam data to equivalent parallel beam projection measurements by a method known as rebinning (Dreike & Boyd, 1976). The rebinned data are then reconstructed using the parallel beam algorithm. Algorithms based on these principles are most commonly used in present day medical scanners since, being noniterative, they involve relatively fewer computations and are less susceptible to noise. In addition, each set of projections can be processed immediately as they are acquired. The latter feature is important in the medical field because of the necessity of on-line diagnosis of the patient's condition.

Algebraic Reconstruction Techniques (ART) fall under a more general class of algorithms called series expansion methods (Gordon, 1974). These methods transform the problem of estimating the linear attenuation coefficients to finding a finite set of numbers through the solution of a set of linear algebraic equations. The image is discretized into a finite number of elements called pixels, with the pixels being identified by their row and column numbers i and j , respectively. The value in each pixel is a number proportional to the linear attenuation coefficient within that pixel. The algorithm begins by guessing these numbers $A(i, j)$ for all the pixels, and then modifies each element along each ray by a factor that compensates for the discrepancy between the measured ray sum $P(l, \theta)$ and the calculated ray sum $R(l, \theta)$. Two forms of ART can be differentiated depending upon the method used for correcting the pixel values. In additive ART the correction is based on :

$$A^{n+1}(i, j) = \max \{A^n(i, j) + (P(l, \theta) - R(l, \theta))/N_{(l, \theta)}, 0\} \quad (7)$$

where $N_{(l, \theta)}$ is the number of pixels that lie along the projection under consideration. The multiplicative form of ART uses the expression :

$$A^{n+1}(i, j) = A^n(i, j) \frac{P(l, \theta)}{R(l, \theta)} \quad (8)$$

If the calculated ray sum is the same as the measured one, then the assumed values are taken to be the correct ones for that projection. However, if for some other projection there is a large error, then the picture elements of the last projection which lie in the ray for a

new projection are modified as required by the discrepancy between the calculated and the measured value. Thus, each projection in each view is examined and values of $A(i, j)$ are changed in an iterative manner. These algorithms require relatively more computations and are susceptible to noise. In return, they are more tolerant to missing data and allow the incorporation of a priori information or constraints.

An algorithm which has found extensive application in emission tomography is the Estimation-Maximization (EM) algorithm. It is based on an exact stochastic model of projection measurements (Dempster et al., 1977) and is an iterative, algebraic technique used to find maximum likelihood estimates from incomplete data. The measured projections are considered to be incomplete data, in the sense that no measurement is completely representative of the system being investigated. Two sample spaces X , and Y , are defined with the observed incomplete data $y \subseteq Y$ having a probability density function $g(y, \theta)$ (either known or assumed), where θ is a vector of parameters to be estimated. The data that one would ideally obtain is referred to as complete data $x \subseteq X$ and is related to y through a mapping $h : X \rightarrow Y$ such that $h(x) = y$. The postulate is that the incomplete data is a subset of the complete (unobserved) data. The criteria for defining the complete data space is based on the physics of the problem. If x has a probability density function $f(x, \theta)$ then

$$g(y, \theta) = \int_{\{x: h(x)=y\}} f(x, \theta) dx \quad (9)$$

x being determined by $y = y(x)$.

The E-M algorithm aims at finding θ which maximizes $g(y, \theta)$ using the density function $f(x, \theta)$. The estimation or the **E** step consists of forming the conditional expectation $E(\ln f(x, \theta) | y, \theta^n)$, where θ^n represents the current estimate of the vector of parameters. The maximization, or the **M** step, chooses θ^{n+1} as the new vector estimate which maximizes the conditional expectation. The new estimate is then used in the **E** step and the process is repeated until the logarithm of the likelihood function, $\ln g(y, \theta)$ is maximized. A comprehensive discussion of the E-M algorithm has been presented by Dempster et al. (1977).

Some of the merits of this algorithm are that it can account for statistical variations, can easily incorporate effects of nonuniform beams and other pathological effects. There is also no need for rebining the fan beam data into parallel beams, and the non-negativity of the final reconstruction is assured. The adaptation of this algorithm to transmission tomography was first accomplished by Lange and Carson (1984). Another advantage in comparison to the transform method based algorithms lies in the implementation. The mechanics of the algorithm do not change in accordance with the geometry of data collection. However, the algorithm does need information to be generated for the geometry of the reconstruction,

Figure 5: Comparison of reconstruction of a phantom using filtered backprojection and the E-M algorithm.

such as the identity of the pixels that intersect each beam in each view as well as the length of intersection of the beams with each of those pixels.

We have tested the capabilities of the above algorithms for image reconstruction on both simulated as well as measured projections of a number of static density distributions. Objects for testing the reconstruction accuracy of the algorithms, or the imaging capabilities of tomographic scanners, are referred to as phantoms. For comparing the accuracy of reconstruction of the filtered back-projection and the E-M algorithm, the parallel beam projections for an ellipse with a uniform attenuation coefficient of 2 density units were simulated. The number of views simulated were 45 over 180° and the number of beams in one view were 24. The major and minor axis of the ellipse was 0.96 and 0.62 length units, respectively. The region of reconstruction was subdivided into 24×24 pixels leading to a spatial resolution of 0.0833 length units. Ideal conditions are assumed so that there is no noise included in the simulated projection measurements. The Filtered Back Projection algorithm for parallel beam geometry and the E-M algorithm were implemented as part of the development of a CT scanner in our laboratory. Figures 5 (a) and (b) illustrate the reconstruction obtained by Filtered Back Projection and the EM algorithm, respectively. The expected reconstruction is an image of an ellipse with pixels indicating an attenuation coefficient close to 2.0. With the reconstruction made by using the Filtered Backprojection there is what is referred to as the cupping artifact (the lower densities in the middle). With the reconstruction made by the E-M algorithm there is uniformity in the reconstructed value in the pixels with the magnitudes ranging from 1.8 to 2.1.

The reconstruction capabilities of the algorithms are also assessed by comparing the images reconstructed from the projections measured for an actual phantom using the CT scanner in our laboratory. A description of the CT scanner and its capabilities is deferred

to a later section of the chapter. The transmission data for a plexiglas column of 0.19 m internal diameter filled with water was acquired over 90 views with 39 projections each. It has to be noted that the water in the column is static (no flow). The image was reconstructed via the Snark89 (Herman et al., 1989) image reconstruction package using the convolution method for divergent beam projection data as well as by an additive algebraic reconstruction algorithm (ART). These are compared with the image reconstructed by the E-M algorithm in Fig. 6. The reconstructed number in each pixel should ideally be $0.086 \text{ cm}^2/\text{g}$, corresponding to the mass attenuation coefficient of water at 660 keV which is the peak energy of the radiation from the Cs-137 radiation source used in the scanner. Although visually the

Figure 6: Comparison of reconstructions from different algorithms, (a) Convolution-Backprojection, (b) Additive ART, (c) E-M algorithm.

reconstruction by the convolution method appears to be better, quantitative comparison between the reconstructions has to be made on the basis of the magnitudes assigned to the color bar. The mean attenuation coefficient, and the deviation from the mean, obtained using the three algorithms are reported in Table 2.3. The mean reconstructed value obtained using the traditionally used algorithms are far away from the desired value of $0.086 \text{ cm}^2/\text{g}$

and the spread in the pixel values is much larger. The uniformity of the reconstruction by the E-M algorithm can be judged on the basis of the corresponding numbers in the table.

Table 1: Mean and standard deviation of attenuation coefficients reconstructed by the three algorithms

Algorithm	Reconstructed Mean	Std. Dev.
Convolution	0.0736	0.060
ART	0.0728	0.030
E-M Algorithm	0.0887	0.003

3 Hardware Elements for a CT Scanner

The two primary elements of a CT scanner are the radiation detectors and the source of radiation. There are two main types of detectors, the classification depends on the principle used in the detection process. In the detectors of the ionization chamber type, the sensors react to the ionization produced in them by the radiation. In the scintillation type detectors, excitation or molecular dissociation induced by the radiation produces the measured effect. For transmission type CT scanners the scintillation detectors are extensively used. These detectors are actually a combination of a scintillation crystal, a photocathode and a photomultiplier that produces a voltage proportional to the intensity of the incident radiation. These kind of detectors have the capacity to handle count-rates of up to 10^{10} events per second. For steady state measurements thallium activated sodium iodide crystal is commonly used owing to a very high conversion efficiency and a short decay time (10^{-7} s). For transient measurements, however, some organic materials such as anthracene and stilbene are used because of their short recovery times. They, however, have a relatively low conversion efficiency.

The two types of radiation that can be employed in CT scanners are X-rays and gamma rays. Both of them consist of what are referred to as photons which are packets (quantum) of electromagnetic radiation with neither charge nor mass. Hence, X-rays and gamma rays are physically identical differing only in their origin. X-rays result from the bombardment of a target with high speed electrons and, therefore, X-ray machines are essentially electron accelerators. A high energy electron beam is converted into X-rays by making use of a suitable target material. The efficiency of this conversion process is low being of the order of 10% or less. The characteristics of the X-ray energy depends on the nature of the target

material used in the X-ray tube. Tungsten and molybdenum are the most commonly used target materials. Since the mass absorption coefficient for an X-ray is inversely proportional to the one-third power of the X-ray energy, a suitable choice of the energy is required to obtain optimum attenuation of the X-ray beam. The following table lists the transmittance i. e. the fraction of the initial intensity that emerges without attenuation for an X-ray beam at different energy levels.

Table 2: Transmittance of X-ray at different energy levels

Energy - keV	Depth of water - cm	
	1.0	0.1
5	0.017	0.66
6	0.087	0.78
8	0.34	0.90
10	0.56	0.94

Most often the characteristic energy of the photons emerging out of an X-ray tube are relatively low. At low energies the proportion of the photons that are removed from the beam is higher. A 1 cm thick steel specimen will attenuate the intensity to only about 10 % of the initial intensity at 100 keV, 30 % at 200 keV and 50 % at 500 keV. In order to be able to study large test sections it then becomes necessary to have photons of higher characteristic energy. Radioisotopes that emit gamma rays typically have higher characteristic energy and are to be preferred over X-ray tubes for process engineering tomography.

The number of photons emitted by a radioisotope is proportional to the number of disintegrations. This decay rate is usually expressed in Curies which is equivalent to 3.7×10^{10} disintegrations per second. Since the emission of radiation from radioisotopes is isotropic, only a fraction of the disintegrations can be used for measurement purposes. A typical solid angle factor is 10^{-5} . With the use of collimation for the source as well as for the detectors in CT scanners, the number of photons that could be available is further reduced. There are two types of radioisotopes that can be used as a source of gamma radiation. These are the separated fission products, such as Cesium-137, and isotopes that are made active by neutron bombardment. Most often the cost of the former type of sources tends to be high and, depending on the application, the latter type of isotopes are more commonly used. The choice of the source strength depends on the application and the accuracy desired. If steady state measurements are adequate, then strengths in the millicurie range suffice. However, if transient measurements in process systems of a couple of feet in diameter are required, then source strengths of at least 5 Curies might be necessary. This amount of radioactivity can

raise serious safety considerations, and extensive measures for handling such a system would have to be incorporated in the facility. The choice of a particular isotope also depends on its half-life, the decay pattern, and also the photon energy and its distribution. A reasonably long half-life period is desirable in order to avoid frequent recalibrations due to decay in source strength. The decay pattern of the isotope needs to be considered for evaluating the ratio of beta to gamma radiation as well as for the determination of the properties of the associated secondary radiation. The peak energy of the photons should be high enough to give a not too small value of the transmission ratio I/I_0 . It is also desirable that the distribution of the photon energies be unimodal and as narrow as possible. This reduces the effects of polychromaticity of the beam and the beam hardening artifacts in the final reconstructed image.

In addition to the source and the detectors, the other hardware required for a CT scanner consists of : collimators, the positioning system for orienting the source-detector assembly with respect to the system being imaged, the data acquisition and signal processing system, and a host computer. Medical CT scanners are designed for imaging the internals of the human body. Thus, the orientation of these scanners is such that the imaging process can be carried out when the person is lying down. In process systems most often the test sections of interest are vertical, and, consequently, medical scanners with the design mentioned above are not suitable for use. Scanners for use in process engineering applications are typically designed in house. Therefore, the hardware, as well as the associated signal processing and data acquisition system, for the CT scanner that was developed in the our laboratory serves as an example and is described below.

3.1 The CT Scanner at CREL

CT scanners with the fourth generation scanning configuration (fixed detector-rotating source) are capable of providing temporal resolution of the order of seconds. The hardware for such a scanner is simpler since it is only the source that rotates. Consequently, the inertia of the system is very low and therefore the demands on the rotary positioning device is not high. However, the detectors in such a scanner cannot be collimated since they have to be able to detect rays from a large number of directions. The probability of scattered radiation corrupting the attenuation measurements is high. In addition, the number of detectors that are required is very large leading to a very expensive system. Therefore, the third generation configuration was adopted for our scanner. In this scanning configuration the entire arrangement of the detectors, source and collimators has to be rotated around the test section. Since the inertia of the system to be moved in this configuration is large, a temporal resolution of the order of a few seconds cannot be expected. A schematic of the scanner developed at the

Chemical Reaction Engineering Laboratory (CREL), Washington University, in St. Louis, is illustrated in Fig. 7.

Central to the unit is the scanning assembly consisting of a rotation stage (gantry) on which an array of eleven scintillation detectors is mounted on one side and a source holder on the opposite side of the test section. The whole assembly of the detectors and the source can be rotated about the axis of the test section through a stepper motor interfaced to a host computer. A resolution of 0.1° can be achieved by the rotary positioning system. Consequently, there is no serious limitation on the number of views that can be obtained to reconstruct the image of the cross section. The optimum number of views required is dictated primarily by the desired density resolution, and increases with the demand for a higher resolution. The source used is an encapsulated 100 mCi Cesium-137 isotope. The encapsulation is such that it provides a fan beam subtending an angle of 40° in the horizontal plane. The source has been further collimated using a $20 \times 10 \times 10$ cm lead brick with a central slit such that the emerging beam has a thickness of 6.5 mm at a distance of 28 cm from the source. This amount of source collimation was required in order to reduce the background counts to less than 5% of the counts measured in air. The detectors used are $2'' \times 2''$ NaI scintillation detectors. The arc in which the detectors are set has a radius of 0.923 m. This radius was necessary to accommodate test sections as large as 0.35 m in diameter. Given this radius and the size of the detectors only eleven of them could be accommodated in the fan beam arc of 40° . If one were to use the system in this configuration there would be only eleven chordal transmittance measurements (with the number going down as the size of the test section is reduced) leading not only to a coarse spatial resolution but also to severe aliasing as indicated by signal sampling considerations. The number of detectors in the arc were therefore effectively increased by making use of a collimator, which for a given view moves across the detector arc, so that each detector samples multiple rays. This however, leads to increased scanning time (the scanning time increases in proportion to the number of additional rays sampled by a detector). The movement of the collimator is achieved by another independent stepper motor, also interfaced with the host computer. The collimator made of lead is 6.35 cm deep and has a height of 7.62 cm. The detectors are completely shielded by the collimator. The collimator has rectangular holes 5×10 mm at locations appropriate to each of the detectors. These dimensions for the collimator holes were optimized based on considerations of providing adequate area for detecting photons with good statistics in the chosen sampling period. The entire scanning assembly weighs about 90 kgs, and consequently the maximum rotational speed that can be achieved is about 1 r.p.m. This implies that the temporal resolution of the scanner is not adequate for detecting transients in the flow. Adequate care has been taken in choosing gears with

Figure 7: Schematic of the CT Scanner.

negligible backlash so that the motion of the collimator, and that of the scanning assembly as a whole, can be controlled with precision and accuracy. The entire scanning assembly has a central opening large enough for it to translate up and down with respect to the test section. This latter motion is achieved by means of four precision square threaded screws supporting the scanning assembly at the corners. They can be driven synchronously to accomplish the axial positioning required for scanning different horizontal sections of the column. The system also incorporates adequate shielding using lead bricks for radiation safety.

4 The Signal Processing and Data Acquisition System

Gamma photons randomly emitted from the source get attenuated in number proportional to the holdup distribution that the beam encounters as it traverses the test section. Each photon entering the detector crystal produces a light pulse, which is sensed and amplified by a ten stage photomultiplier tube integrated with the detector. The biasing of the cathodes of the detectors (1000 Volts) is provided by two high voltage power supplies (Canberra, Model 3002D). The voltage pulses are amplified using timing filter amplifiers (Canberra 2111). The amplifiers accept positive or negative current pulses from the detectors and deliver output pulses in the range of $\pm 5V$ range. They have independent adjustments for the differential and integral time constants in their RC-CR circuits. These controls enable one to shorten the tail of the signal pulse and to choose a suitable amplitude, respectively. The power to the amplifiers is fed by NIM/BIN power supplies (Canberra 2000). The signals from the amplifiers are fed to discriminators to eliminate undesired secondary emissions. The threshold for the discriminators is continuously adjustable from 15 mV to 1 V either by a potentiometer on the front panel or by software control. A threshold voltage of 45 mV was found to be adequate for removing most of the secondary emissions. Thus, the discriminator produces a logic pulse corresponding only to those photons depositing their full energy in the detector. The logic pulses are counted directly using a multichannel 24 bit scaler (binary counter). The scaler also carries a temporary buffer corresponding to each channel for storing the accumulated counts. A function generator inputs a sine wave at a known frequency to one of the channels of the scaler as a reference input for error control. A list sequencing crate controller with 8K FIFO (first in - first out) memory serves as a buffer when the contents of the scaler are emptied at user specified sampling rates. When the FIFO memory is half full a CAMAC (Computer Automated Measurement and Control) crate controller transfers its contents to the host computer hard disk via a GPIB (General Purpose Interface Bus (IEEE 488)). The transfer from the scaler buffer to the FIFO memory, as well as the transfer from

the FIFO memory to the computer memory and later to the hard disk, proceed in parallel with no data loss. The advantage of using CAMAC instead of A/D converters is that it allows a wide range of modular instruments to be interfaced to a standardized crate. The crate has a dataway that provides a pathway between the modules and a host computer. The crate has a number of stations in which different modules (such as scalers, discriminators etc.) can be inserted. The last two stations of the crate are meant for crate controllers whose purpose is to issue commands to the modules and also transfer information between the modules and the host computer.

Also embedded in the acquisition process is the control of the motion of the stepper motors required for the positioning of the collimator (for obtaining different rays in a given view) and the scanning assembly as a whole (for obtaining different views). The two stepper motors (Superior Electric, M092-FD-8009) have independent indexers (Superior Electric Model 430-PT) that are interfaced to the host computer using RS232 communication. All the motion control commands are loaded into the memory of the indexers. Upon receiving a signal issued by the computer at the appropriate instants of time, that are coded into the data acquisition program, the stepper motors induce the required motions. Thus, the entire process of acquiring all the data required for the imaging of a cross section is completely automated.

5 Measures of CT Scanner Performance

The main factors that determine the imaging capabilities of a CT scanner used in engineering applications are its achievable spatial, temporal and density resolution. The spatial resolution of any imaging system is defined as the minimum distance that two high contrast point objects can be separated by, in order for the imaging system to perceive them distinctly. A measure of the spatial resolution is the point spread function (PSF) which is the extent to which the image of a point object would be blurred. The width of the PSF at half its maximum value, known as full-width-at-half-maximum (FWHM), is the criterion most commonly used for specifying the resolving power of an imaging system (Glover and Eisner, 1979). It should be noted that two PSF's may have the same FWHM but different shapes and, therefore, in specifying the resolution it is necessary to indicate the complete PSF rather than just the FWHM. For most imaging systems the PSF is a function of position and may vary from the center to the periphery of the image. It is however, desirable to have an approximately isotropic PSF and this is often achieved in well designed CT scanners. A simple method of measuring the PSF of a CT scanner is to image a phantom consisting of an object that is dense and narrow (eg. a thin steel wire) that is positioned perpendicular

to the imaging plane. Imaging a number of such infinitesimal point objects interspersed at several locations in the plane would enable the determination of the variation in the PSF. The most significant factors that affect the PSF of a CT scanner are geometric factors, and the reconstruction algorithm. The geometric factors that affect the resolution are the focal spot size of the X-ray tube (the size of the isotope for a γ ray source), the aperture of the detectors, the magnification factor and the spatial sampling rate. The magnification factor is the ratio of the focal spot-detector distance to the focal spot-object distance. Since in practice both the focal spot and the detector aperture are finite, the region subtended between the two is trapezoidal as shown in Fig. 8a. The measured attenuation profile of an elementary object depends on the position of the object within the trapezoidal region. Assuming a uniform focal spot intensity distribution, and a uniform detector response, the measured attenuation profile of the elementary object is either trapezoidal, or triangular as shown in Fig. 8b. Thus, the image of a point object is broadened by the finite width of the focal spot and the detector aperture. A measure of this blurring in terms of the dimensions

Figure 8: (a) Geometry for attenuation profiles at different positions between the source and detector; (b) Attenuation profiles for an elementary point object at different points along the trapezium

of the focal spot size s , the detector aperture d_a and the magnification factor M has been derived by Yester and Barnes (1977) as :

$$d_{eff} = \frac{1}{M} \sqrt{d_a^2 + (M - 1)^2 s^2} \quad (10)$$

where d_{eff} is the effective detector aperture width, which is related to the approximate width of the blurred image of the point. This expression dictates that the focal spot and the detector aperture be reduced in order to reduce the FWHM of the PSF. For purposes of providing an adequate area for photon detection in order to have faster data acquisition rates it is desirable to have a large detector aperture. Hence, there needs to be some compromise between the two conflicting requirements. In addition, the PSF is also dependent on the frequency of spatial sampling. The interaction between the various parameters affecting spatial resolution has been investigated comprehensively by Yester and Barnes (1977). Their results indicate that the spatial sampling interval need be no smaller than the focal spot size. In fact, a degradation of the PSF is seen with increase in the spatial sampling frequency. More on the requirements of spatial sampling will be discussed in connection with aliasing artifacts.

The temporal resolution refers to the frequency with which the images can be obtained. For process systems it is desirable to have the measurements completed rapidly so that the time evolution of the flow phenomena can be studied. With X-ray and gamma ray tomography the data obtained for the concentration distribution of phases is almost always time averaged, since it generally requires a significant period of time to obtain the photon count rates for all the projections in a significant number of views with good photon counting statistics. Depending on the design of the scanner this period can range anywhere from a few minutes to close to an hour. This is a basic limitation of X-ray and gamma ray tomography with the scanner designed with the fan-beam scanning geometry. With the recent advent of impedance tomography techniques it has become possible to obtain time resolved measurements, since in these systems there is no need for physically rotating the sensors and the source, as is required in X-ray and gamma ray CT systems.

The density resolution of a CT system refers to the smallest difference in mass attenuation coefficients that the system is able to distinguish. The standard deviation of the statistical distribution of the density in each pixel based on a constant object cross-sectional density of 1 g/cm^3 can be used as a measure of the density resolution of the system. The single important factor that determines the density resolution is the random fluctuations in the photon counts delivered by the X-ray tube or the gamma ray source. This is because the difference in photon counts caused by a difference in mass attenuation coefficient of the materials in the path of the beam has to be significantly higher than the fluctuations in the photon count rate. The higher the intensity of the radiation, the smaller is the standard deviation of the photon count rate and the better the density resolution is. Having a higher intensity of radiation is, however, not desirable owing to safety considerations.

Different authors have derived different expressions for a quantity that serves as a measure of the density resolution that accounts only for photon counting statistics. Shepp and Logan

(1974) have derived the following expression for the density resolution :

$$\sigma^2 = \frac{4}{I_d (\log \frac{I_d}{I_e})^2} \quad (11)$$

where I_d and I_e are the number of detected and emitted photons, respectively. De Vuono (1979) has derived an expression for the density resolution obtainable from all the measurements in an entire scan as follows :

$$\frac{\sigma_\rho}{\rho} = \frac{n}{2 \mu_w \rho_w d_i \sqrt{m N}} \quad (12)$$

where n is the number of beams in each view, m is the number of views, N is the average number of photons detectable per beam, μ_w is the mass attenuation coefficient of water and ρ_w is the density of water. The above expression involves a constant that has been set to 0.5.

It is clear from the above expressions that improvements in density resolution can be obtained by increases in the number of views obtained in the scan as well as by an increase in the number of detected (and hence the emitted) photons. Any increase in the number of views increases the scanning time. With X-ray tubes it is relatively easy to improve upon the count rates since it is just a matter of increasing the input voltage to the tube. This, however, is not the case with gamma ray sources since the emission rate of photons is fixed by the source activity and decay rate. In order that the reduction in photon count rate due to radioactive decay is not significant during the scanning process, isotopes with a significantly large half-life have to be used.

6 Sources of Error in CT Scanning

The process of CT scanning from measurement of the photon count rate to final reconstruction and display of the image is subject to a set of problems that lead to artifacts or errors in the final result. Some of the problems that can arise include misalignment in the hardware configuration, noisy measurements, and sometimes a poor choice of the reconstruction algorithm and its parameters.

The following is a list of possible sources of error in the experimental procedure from scanning to final reconstruction :

- Geometric misalignment artifacts
- Statistical uncertainty in photon counts
- Compton scattering effects

- Beam hardening effects
- Data sampling frequency in space
- Dynamic bias or void fluctuation effects
- Errors in the image reconstruction process
- Errors and variations in detectors and source

Geometric misalignment artifacts

The mechanical components of a CT scanner need to be well designed to provide great precision and accuracy in the positioning of the detector array and the source of radiation with respect to the test section. Most often it is difficult to ensure that the mechanical center of rotation coincides with the center of the coordinate system used in the reconstruction process. This leads to an incorrect calculation of the contribution of the projections to the pixels that are not truly in the beam path. The problem is especially serious in systems that make use of algorithms that involve the backprojection process such as the Filtered Back-projection algorithm. This calls for accurately locating the center of rotation of the system. This is rather problematic since physical measurements are prone to error. For the CT scanner in our laboratory this measurement has been made within a range of $\pm 1\text{ mm}$ and this, coupled with the use of the E-M algorithm that does not make use of the back-projection process, appears to provide reasonably accurate reconstructions. Instead of making an accurate measurement of the center of rotation Azevedo et al. (1990) suggest the determination of the center from the reconstructed image of a simple phantom by adopting a least squares technique. It is based on the principle that the center of mass of the object projects into the center of mass in each view. The method determines the center of rotation based on the least squares sinusoidal fit to the row wise centers of mass in the reconstructed image. The claim is that this is a robust method that matches experimental measurements as long as noise levels in the image are not high.

Uncertainties due to the Statistical Nature of the Source

Statistical noise in CT images arises out of the random fluctuations that occur in the counting of photons. This is an inherent limitation of the process and the relative accuracy of measurement can be increased only by an increase in the number of detected photons. Another measure that is adopted is to consider the average of a series of samples as a single measurement. Thus, the number of photons obtained for a projection are taken to be the mean of N observations. If $\overline{C_n}$ denotes the mean number of counts, then Barret (1974) specifies that the following criteria need be satisfied for reducing the error due to counting and source fluctuation effects : N is large; $\overline{C_n} \gg 1$ and $1/\overline{C_n^2} \ll 1$. An increase in the number of detected photons, however, is in contradiction to the requirements of reducing the

exposure from radiation due to safety consideration, and averaging a series of samples leads to an increase in the scan time. Optimum source strengths (or X-ray tube output) and a reasonable number of samples have to be found for each application. The CT scanner in our laboratory makes use of a Cesium-137 source of 100 mCi activity, and each measurement is taken to be the average of 54 samples obtained at the rate of 10 Hz, so that each projection measurement is averaged over a period of approximately 6 seconds.

Compton Scattering Effects

The interaction of radiation (X-ray or gamma ray) with matter can be either in the form of attenuation or in the form of scattering. With attenuation a photon is considered to be removed from the beam of radiation completely. In Compton scattering on the other hand, the photons are not removed from the beam but instead have a lower energy than before and their direction of travel is also altered. The Beer-Lamberts' law can be used for the measurement of holdup only in the presence of attenuation. However, the probability of detecting a scattered photon along with the unattenuated photons in a beam is non-zero and this leads to an attenuation coefficient that is lower than the actual value. To minimize the errors due to Compton scattering it is necessary to take into consideration only those photons that are at or near their unattenuated energy level. The ideal way to approach the problem is to use a multi-channel analyzer that not only counts the photons but also provides a measure of the associated energy. However, it suffices to make use of a discriminator that produces a logic pulse only for those unscattered photons depositing their full energy in the detectors. In addition, the probability of detecting a scattered photon is reduced by collimating the beam. The detectors are provided with collimators made of lead or tungsten, or even steel, which are about 2 to 3 inches deep. The width and height of the opening are designed on the basis of the required spatial resolution, the spatial sampling interval and the available photon flux. Thus, due to collimation, scattering is much less of a problem in systems with second and third generation scanning configurations. In fourth generation machines each detector, unlike in the other configurations, needs to accept radiation from a range of angles of incidence making scatter rejection by collimation impossible. In this scanning configuration collimation is provided only along the axial direction so that only those photons that are travelling in a narrow plane are detectable. Swift et al. (1978) have derived the following relation for the measured transmission ratio accounting for the effects of low angle forward scattering of photons:

$$I/I_0 = e^{-\mu l} + \frac{1}{2} \left(\frac{d_a}{x_d} \right)^2 (1 - e^{-\mu l}) \quad (13)$$

where the second term on the right hand side accounts for the scattering effects. d_a and x_d are the detector aperture and the distance of the scattering event from the detector, re-

spectively. For the scanner that was implemented in the authors' laboratory the detector aperture is 5 mm and for the worst case scenario x_d can be only as small as 98 mm, so that the term which determines the extent of the scattering contribution works out to be $0.001307(1 - e^{-\mu l})$ and is very small in comparison to $e^{-\mu l}$.

Beam Hardening Effects

In general the Beer-Lamberts' law for the attenuation of radiation is applicable only for monochromatic emissions from the source of radiation. The radiation from any source is polychromatic, that is to say that the source emits photons of different energies. Consequently, in the passage of a beam of radiation through some material the lower energy photons get attenuated earlier than the higher energy photons and, consequently, the spectrum of the emerging radiation is different from the one that is entering. This makes the object more transparent than it really is (the density is under-estimated) leading to what is referred to as beam hardening artifacts. Beam hardening effects are important only in situations where the spectrum of the source emissions is wide (with two or more peaks) and the object being scanned has materials having vastly different attenuation coefficients like bone and tissue. One of the prime considerations in selecting the radioactive source is, therefore, that its emission spectrum be as narrow as possible, and Cs-137 satisfies this requirement extremely well. X-ray tubes generally provide photons with a significant distribution of energy. The flow structure of multiphase systems do not exhibit the same high gradients in density as is typically encountered in scanning the human head. In these systems a more gradual and often monotonic variation in concentration distribution of the phases is expected. Furthermore the magnitude of the differences in mass attenuation coefficients of the materials involved in flow systems is not as large as in the case of human head (bone and tissue). Consequently, it is reasonable to neglect the effects of beam hardening provided the energy spectrum of the photons has a narrow distribution.

Frequency of Spatial Data Sampling - Effects of Aliasing

The spatial interval with which the projections are required to be sampled depends on the frequency content of the object. The Nyquist theorem states that signal sampling should be at a frequency that is at least twice the maximum frequency present in the system being studied. Thus, if ω is the maximum frequency that is contained in the frequency components of the object, then the projections must be spaced at intervals of $\frac{1}{2\omega}$. However, since there is no a priori information about the flow system, this rule is not convenient to determine the fineness with which the projection measurements are to be made. For a chosen sampling interval the consequence of the object containing frequencies higher than the Nyquist limit is that the information content of the higher frequency components masquerade as those

corresponding to some lower frequency components, and hence the name *aliasing*. It is, therefore, necessary to eliminate all spatial frequencies higher than the Nyquist limit by a filtering operation. With CT scanners the width of the sampled beam itself acts as a filter removing frequencies greater than $1/d_a$ before the sampling process. Thus, aliasing artifacts can be reduced by the proper selection of the beam width (detector aperture). Increasing the beam width, as was discussed earlier, sacrifices the achievable spatial resolution.

The fact that the effects of aliasing are not a serious problem for imaging concentration distribution in multiphase systems is demonstrated with some data obtained with the CT scanner in our laboratory. It has already been described in an earlier section that in this scanner each detector is made to sample 8 beams which works out to angular increments of 0.5° within the fan beam. This spatial sampling interval has been demonstrated to be adequate for the measurement of the holdup distribution in a gas-liquid bubble column. The

Figure 9: Effects of increase in the frequency of spatial sampling of projections.

bubble column diameter is 0.26 m and the projection measurements were obtained by sampling at the above mentioned frequency as well as twice that rate (i.e., at angular increments of 0.5° and 0.25° in the fan beam) for operating conditions that correspond to bubbly and churn turbulent regimes. The measurements were used to compute the transmission ratio

as a function of angular position within the fan beam. The results are illustrated in Fig. 9, where the data corresponding to both sampling rates have been superimposed for the chosen operating conditions of the bubble column. It is observed that essentially no additional information is gained when the projections are sampled at the higher rate. It is expected that this holds true for other multiphase systems, such as gas-solid and gas-solid-liquid systems.

Dynamic Bias or Void Fluctuation Effects

An error that is unique to the probing of two phase flows by radiation techniques is the one associated with dynamic biasing. This arises from the stochastic nature of the emissions from a gamma ray source and the temporal variations of the void fraction. An error free measurement is possible only in the case of a constant source and static void fraction, both of which are not realizable. Because of the exponential attenuation of the radiation traversing a medium, the logarithm of a time averaged measurement is not equal to the time average of the logarithm of the measurement. If the time over which the averaging is performed is small, then the variation in the void fraction within that time interval is small and the static void approximation is valid. On the other hand, the longer the time allowed for the photon counting, the smaller is the error in the counting process due to the statistical nature of the emissions from the source. Most often the sampling time for each projection is adequate to provide good statistics in the photon counting process. The question that remains is whether the void structure is constant within this period of time. Wyman and Harms (1985) have made a thorough theoretical analysis of this aspect and specify the following relation for selecting the observation interval length :

$$t_{obs} = \frac{\lambda t_f \alpha}{u(\lambda, \delta)} \quad (14)$$

where t_{obs} is the optimum sampling period, λ is a factor depending on the size of the test section and the mass attenuation coefficient of the medium in the test section, α is the allowable error in void fraction, t_f is a characteristic time of the fluctuations in the flow, δ is the amplitude of the fluctuations in the voids about the mean and u is a function of λ and δ . Unfortunately, neither δ nor u are known a priori preventing the determination of t_{obs} by this equation for a given flow system. Consequently, the time for sampling each projection measurement was determined for the CT scanner in our laboratory by adopting the simpler approach suggested by Barret (1974). A counting experiment is performed over a long period of time, recording on a time scale the positions at which each count occurs. The effective mean for the whole period is computed. The record of counts over the period is split into a number of subperiods each of duration δt , and the effective mean for that interval is found. This process is repeated for smaller and smaller intervals taking care that the interval is not

made too small for statistical counting errors to arise. The means corresponding to each of the sub-intervals are examined for convergence with respect to the mean for the single long time interval. This simple experiment was done for the flow in an air-water bubble column of 0.27 m in diameter, both at bubbly ($U_g = 0.02$ m/s) and churn turbulent flow conditions ($U_g = 0.08$ m/s), and the chordal void fraction was computed for a few detectors. The results are presented in Table 3 for some arbitrarily chosen rays in the fan beam. The measured chordal void fraction appears to be independent of the sampling period for the tested flow conditions (representative of most flows). Consequently, a sampling period of 0.1 sec was considered to be sufficiently small for making the static void fraction approximation.

Table 3: Measured chordal void fraction for different sampling periods

Flow Regime	Sampling Period - secs	Chordal Void Fraction at		
		0.0°	-7.08°	10.58°
Bubbly Flow	0.1	0.084	0.098	0.080
	0.05	0.084	0.099	0.086
	0.03	0.084	0.102	0.088
Churn Turbulent Flow	0.1	0.250	0.250	0.030
	0.05	0.245	0.258	0.030
	0.03	0.250	0.260	0.032

Errors in Image Reconstruction

In scanners that make use of the Filtered Backprojection algorithm the choice of the filter and its cutoff frequency has a significant impact on the final reconstructed image. The common filters that are used in practice are the Ramp, Hann, Hamming and Parzen (Stanley, 1975). A parameter that is to be set for any such filter is its cutoff frequency. If it is desired to retain high frequency information, then the cutoff frequency is set to a high value. However, it is the high frequency components that are the most susceptible to contamination by noise. Therefore, the noise gets amplified and leads to artifacts referred to as streaks. Schneberk et al. (1990), have studied the effect of the choice of windows and the cutoff frequency on the reconstruction of a point object. Their results indicate that the ramp filter provides the best edge detection (detection of sharp features) capability but at the cost of higher noise amplification. The Parzen filter on the other hand is seen to suppress noise effects but leads to a higher FWHM for the PSF i.e., the spatial resolution is sacrificed. The other two filter

windows are said to provide a performance that is in between the above two. For the imaging of multiphase flow systems the choice of the filter may not be too critical mainly because the information content in the distribution of phases is such that they are identified under any filtering scheme. In addition, the achievable resolution is probably limited by the hardware constraints rather than the choice of filter for reconstruction by the Filtered Backprojection algorithm. For the Algebraic Reconstruction Techniques (ART) and the E-M algorithm there is no parameter such as the cutoff frequency of a filter. The accuracy of reconstruction from these algorithms mainly depends on the accuracy of the measurements, and the accuracy with which the geometry of the data collection with respect to the coordinate system for image reconstruction can be provided as input.

The accuracy of image reconstruction by the E-M algorithm is demonstrated by reconstructing the images from simulated and measured projections of static objects. For both the simulation and measurement a plexiglas column with 0.19 m internal diameter and a wall thickness of 0.635 cm filled with water was considered. The data was simulated using 39 projections per view, and there were 90 such views collected over 220° . The scanner in our laboratory was programmed to get the data in the same manner. The reconstruction was done on 36×36 grid for a spatial resolution of 0.54 cm. Ideally, the reconstruction should yield a value of $0.086 \text{ cm}^2/\text{g}$ in all the pixels, the value corresponding to the mass attenuation coefficient of water at 660 keV which is the peak photon energy of the Cesium-137 isotope. Figures 10 (a) and 10 (b) are the plot of the histograms for the spread of the reconstructed pixel values for the simulated and actually measured data, respectively. The mean and standard deviation of the reconstructed pixel values for the simulated data are 8.65×10^{-2} and 2.51×10^{-3} , respectively. The corresponding quantities for the measured data are 8.73×10^{-2} and 3.73×10^{-3} , respectively. The spread for the simulated data is narrower leading to the conclusion that provided the measured data is accurate the E-M algorithm provides reasonably accurate reconstructions.

Errors and Variations in Detectors and Source

Variations and defects in the detectors or the source of radiation cause errors in the projection measurement. A single detector, and its corresponding data acquisition channel, may be malfunctioning and lead to erroneous measurements in either a single or a set of projections depending on the scanning configuration. In a scanner of the third generation type a defective detector would lead to an incorrect, or a set of incorrect, projections in all the views of the object. This particular beam or set of beams, is tangent to a circle in the image plane and would lead to what is known as ring or circular artifact. With fourth generation scanning a single defective detector leads to all the projections in one view to be in error. The resulting error in reconstruction is far less serious than the ring artifact because it is

(a)

(b)

Figure 10: Spread of attenuation coefficients for water phantom reconstructed for (a) simulated data, (b) measured data

considered that any problem that produces a uniform error throughout a view is far less serious than that which produces a single bad projection in all the views (Shepp and Stein, 1977). The only means of overcoming this error is by identifying the detector in error and either replacing it or setting it right.

Measurement errors are also possible in systems making use of X-ray tubes as the source of radiation. It is assumed that X-ray tubes produce very small temporal and spatial variations in the output X-ray intensity. If there is some variation then the measured photon count rates for I_0 would be a function of time and lead to errors in the computed transmission ratios. Often the X-ray output is monitored by a separate reference detector which rotates with the X-ray tube in a known constant geometric relationship. This, of course, only takes care of temporal variations and if there are spatial variations (the X-ray intensity is not isotropic) then the problem remains. The choice of a well designed X-ray tube that has a reasonably stable output is therefore critical in the design of an X-ray tomographic system. With gamma ray tomography the problem is not so critical especially if the isotope that is used has an extremely long half-life. The Cesium-137 source that is used for the scanner in our laboratory has a half life of 30 years. The unavoidable statistical nature of the emissions is taken care of by making use of a mean photon count rate (average of several samples) which is reproducible.

7 CT Scanner Design Process

In this section we present the steps involved in the choice of the design parameters for a CT scanner. For this we make use of the system in our own laboratory and the system designed by De Vuono (1979) at the Ohio State University, as examples. In the choice of the parameters, it is necessary to take into consideration a number of factors such as cost, source strength (dose rate), space constraints and mechanical considerations. All these factors are affected by the required spatial, temporal and density resolution. An increased spatial resolution calls for an increase in the number of detector channels. An increase in temporal resolution requires faster scanning capabilities, in which case the mechanical positioning devices need to be robust and the system needs to have the abilities to determine the positions of the scanning assembly accurately in a short period of time. All of these increase the cost of the required components. An increase in the density resolution requires an increase in the photon count rates and an increase in the number of views of the object. The former is limited by safety considerations, and the latter increases the scanning time which compromises the temporal resolution.

For the CT system in our laboratory the fourth generation scanning design was excluded

due to space and cost considerations. The number of detectors required for such a system would be at least a 100, and, the cost of the system increases dramatically with increase in the number of detectors. In addition, to accomodate test sections as large as 18 inches in diameter, the required space would be approximately $8' \times 8'$, while we had a space constraint of $5' \times 5'$. The choice of the fan beam rotating source-detector system (third generation scanning) system meant that temporal resolution had to be sacrificed. We list the set of constraints and requirements for the design of the scanner below :

Spatial Resolution : 5 mm

Density Resolution : 0.05 g/cm^3

Scanning Time for a Column of 6" in diameter : 45 minutes

Maximum Allowable Source Strength : 100 mCi

The source-detector arc radius is generally set to be approximately twice the diameter of the largest test section to be scanned. In our case this radius worked out to 92.3 cm. The encapsulated Cs-137 source obtained from Kay-Ray Sensal, Mt. Prospect, IL has a fan beam angle of 40° . In order for the fan-beam to span the largest test section of 18" in diameter, the distance of the source from the center of the test section was determined to be 59.69 cm. This gives an average magnification factor M of 1.56. For a spatial resolution of approximately 5 mm the detector aperture can be computed using Eq. 10 in which the source width is 3 mm corresponding to diameter of the Cs-137 isotope. The aperture width that is computed is 7.5 mm. The aperture width that was chosen was, however, 5 mm, which means that our spatial resolution can be better than 5 mm. The height of the aperture was set to twice the aperture width following standard practice.

The number of projections (beams) per view that is required depends on aliasing considerations. To ensure adequate sampling of the flow domain it is, ideally, desirable that the successive beams in a view overlap or at least are close to each other. As was mentioned earlier, each detector was made to sample multiple beams by the use of a movable collimator that sweeps across the face of the detector array. The increment in the movement of the collimator was designed to be 0.5° . This corresponds to a linear movement of approximately 5 mm at the center of the test section which is close to the beam width at that location. We have demonstrated that this spatial sampling frequency results in no aliasing artifacts. The number of views required depends on the chosen number of projections per view and the required density resolution. Brooks and Di Chiro (1976) have established the criterion that the number of views m satisfy $m \geq n\pi/2$. For a column of 6" diameter the number of projections per view required is 26, and therefore the number of views in a scan of 180° is 49. This is true for parallel beam scanning for which the scans are obtained over 180° . With

fan-beam geometry however, it is necessary to scan over an angle of $180^\circ +$ the fan-beam angle (Peters and Lewitt, 1977) (40° in our case). The number of views required is, therefore, approximately 60.

Having fixed the number of beams per view and the total number of views, one can now use the criterion for density resolution derived by De Vuono (Eq. 12) to calculate the photon count rates required and, hence, the required source strength. For a density resolution of 5 to 6 % with $m = 60$ and $n = 26$ for a 6" column full of water the required number of counts (computed from Eq. 12) is approximately 525. The photon counting time was selected to be 0.2 seconds, so that the total scanning time for a column of this size is about 45 to 50 minutes. The photon count rate required, therefore, is 2625 counts/sec. Since the maximum attenuation will be along the centerline of the test section, the source strength computations are made on the basis that this count rate is required along the centerline.

The measured count rate is a function of the source strength, the degree of collimation, the attenuation properties of the materials in the beam path, the sampling time and the efficiency of detection of the radiation sensors. The measured photon counts can be expressed as

$$N = S_o \tau \epsilon \Omega e^{-(\mu_p \rho_p (d_o - d_i) + \mu_w \rho_w d_i)} \quad (15)$$

where N is the number of photon counts in a given period of time (τ), S_o is the source strength expressed in photons/sec, ϵ is an overall efficiency factor for photon detection, Ω is the solid angle subtended by the detector aperture at the source and represents the effects of collimation, μ_p and μ_w are the mass attenuation coefficients (cm^2/g) of the pipe material and water respectively, and, d_o and d_i are the outer and inner diameters of the pipe. This expression is used for calculating the source strength, given the required photon count rate, the collimator dimensions, and the material properties of the pipe and the fluids involved in the experiment.

Since a point source emits radiation isotropically, only a fraction of the emitted photons can enter the detector aperture. This fraction is represented by the solid angle subtended by the detector at the source and can be defined as (Tsoulfanidis, 1983) as the ratio of the number of particles per second emitted inside the space defined by the contours of the source and detector aperture to the number of particles per second emitted by the source.

For the present geometry, in which the detector aperture is a rectangle with a width of $2a$ and $2b$, and the source detector distance is d , the solid angle is given by (Tsoulfanidis, 1983) :

$$\Omega = \arctan \frac{ab}{d \sqrt{a^2 + b^2 + d^2}} \quad (16)$$

This expression holds for the situation where the source is on the axis of the rectangular aperture. Using this expression the solid angle is calculated to be 8.4×10^{-4} .

The detector efficiency gives the fraction of particles impinging on the detector that are recorded per unit time by the detector. It depends on the density and size of the detector material, the type and energy of radiation and the associated electronics. The simplest and most accurate method of measuring the detector efficiency is to record the number of photon counts in a given period of time for a calibrated source (Tsoulfanidis, 1983). If the obtained count rate is r (counts/sec), the equation for the efficiency is

$$\epsilon = \frac{r}{S \Omega \tau} \quad (17)$$

where τ is the sampling time. In an earlier section it was mentioned that in order to detect only those photons that deposit their complete energy in the detector (unscattered photons) the threshold voltage (above which the signal corresponding to a photon detection is considered to be for an unscattered photon) is set to a relatively higher magnitude. Thus, with a calibrated source the overall efficiency of detection was measured to be approximately 0.3 %. This value of the efficiency is low since we are gating in only on those photons that deposit their complete energy in the detector thereby minimizing the effects of Compton scattering. For a plexiglas column of 6" outer diameter, having a wall thickness of 0.25 inches, d_o and d_i are 15.24 cm and 13.97 cm, respectively. For a sampling interval of 0.2 seconds the required source strength is therefore approximately 100 mCi.

A similar case study has been presented by De Vuono (1979) for the design of a fourth generation scanning system. The assumptions made in that study was that the object is scanned over 180° and the number of views taken are equal to $m = \frac{3\pi n}{5}$ with n the number of beams per view equal to $d_i/\Delta x$, where Δx is the desired spatial resolution. The source ring and detector ring diameter are chosen to be twice and thrice the inside diameter of the pipe respectively. The physical detector area facing the source is $2.5 \Delta x \times 5 \Delta x$. The collimation used is different from the usual design having a single circular or rectangular beam. Instead the design of the collimator is such that the radiation impinging on an entire detector is broken up into several beams i.e., the collimator has a multi hole design. The effective detector area is therefore reduced, but an effective aperture width for use in Eq. 10 for calculating the achievable spatial resolution is not clear. It appears that the required spatial resolution is used in deciding on the number of beams per view. For a column with an internal and external diameter d_i and d_o , respectively, an expression for the number of

counts in terms of some of the parameters mentioned above is derived as :

$$N = \left(\frac{5 \epsilon S \tau}{6 \pi^2} \right) \left(\frac{\Delta x^3}{d_i} \right) e^{-(\mu_p \rho_p (d_o - d_i) + \mu_w \rho_w d_i)} \quad (18)$$

where τ in this case is the total scanning time defined as $\tau = m \tau_d$ where τ_d is the sampling time per beam. This equation, along with Eq. 12 for the density resolution, can be used to compute the required parameters for a given set of requirements and constraints.

The preset parameters are :

1. $d_i = 28.89 \text{ cm}$
2. $d_o = 32.38 \text{ cm}$
3. $\tau = 0.1 \text{ sec}$
4. $\Delta x = 1 \text{ cm}$
5. $\sigma_\rho = 0.05 \text{ g/cm}^3$
6. $S \leq 1 \text{ Ci}$

The assumptions are :

1. 180° scan
2. 30 % collimator blockage
3. $\epsilon = 0.75$

It has to be noted that the assumed detector efficiency is very high in comparison to what was measured in our laboratory. We can only hypothesize that the thresholding used for discrimination between scattered and unscattered photons was low and consequently, the calculated strength of the required source will be low.

From the assumptions above,

$$n = \frac{d_i}{\Delta x} = 29 \text{ beams/view}$$

and

$$m = \frac{3 \pi n}{5} = 55 \text{ views}$$

Note the relatively smaller number of beams per view as well as the number of views for a column of approximately 11.5 inches in diameter. This can be partially attributed to the relatively coarse spatial resolution that was desired.

The number of detectors in a fourth generation scanning system is dependent on the number of views. The number of views calculated above was for a 180° scan, hence, the number of detectors required in the entire circle is twice the number of views. Therefore the number of detectors required is 110.

The area of the detector is :

$$A_d = \frac{25}{2} \Delta x^2 = 12.5 \text{ cm}^2$$

and the actual area for detection after collimation is

$$A_a = 0.7 A_d = 8.75 \text{ cm}^2$$

In comparison, the aperture area for a detector in our scanner is 0.5 cm^2 . With $\mu_p \rho_p = 0.5678 \text{ cm}^{-1}$ (stainless steel pipe) and $\mu_w \rho_w = 0.0865 \text{ cm}^{-1}$ (for water) the calculated source strength is 3.17 Curies. It has to be noted that this source strength is high inspite of the low spatial resolution because the required temporal resolution is small. Since the design specification for source strength is violated, Δx was relaxed to 2 cm and with all the other parameters unchanged the recalculated source strength is 198 mCi. With Δx increased to 2 cm , A_a is now 35 cm^2 . Although this source strength was acceptable from design considerations, the resulting count rate of 4×10^5 cps is restrictive for most signal amplifiers. The spatial resolution was then relaxed to 3.5 cm ($A_a = 107.2 \text{ cm}^2$) and the density resolution to 0.06 g/cm^3 . With the new parameters the new source strength required is only 14.7 mCi. The maximum count rate is now reduced to 9×10^4 cps. The reset values for the number of beams per view is 9 and the required number of views is 16. The total number of detectors now required is only 32. The required detector dimensions are $3.4'' \times 6.9'' \times 2''$. The total scan time being 0.1 sec, the scan speed works out to be 300 rpm.

From the above two examples it is clear that the design for the parameters of a CT scanner involves a number of compromises. In the first example the spatial resolution was given precedence over temporal resolution, while in the second case the temporal resolution was of prime concern. The density resolution in both cases was approximately the same, although in the second case it is not obvious if the desired density resolution was achieved in the scanner, since the number of views was only 16. It is also not clear what the effect of the multi-hole collimator design has on the spatial resolution of the system. The above design procedure is summarized in the following steps :

- Choose the type of scanning configuration desired. The general rule of thumb is that if temporal resolution needs to be high then the fourth generation scanning needs to be adopted.
- Set desired values for spatial, density and temporal resolution. An upper limit for the source strength needs to be determined based on safety considerations.
- Some details about the kind of source to be used need to be known at this juncture. Specifically, the source aperture and the fan-beam angle needs to be known.
- The source-detector and source-object distance must now be fixed. The magnification factor M can then be computed as the ratio of the source-detector distance to the source-object distance. Since the object (in our case a pipe of certain diameter) has a finite dimension, an average magnification factor can be computed using the distance of center of the pipe from the source as the source-object distance.
- The required detector aperture can then be calculated using the equation for the point spread function derived by Yester and Barnes (1977) (Eq. 10):

$$d_{eff} = \frac{1}{M} \sqrt{d_a^2 + (M - 1)^2 s^2}$$

where d_{eff} is set to the desired spatial resolution, and s the focal spot width.

- Based on the test-section diameter and the detector aperture the number of beams, n , in one view can be calculated. The number of beams has to be sufficiently large to avoid aliasing artifacts. The number of views, m , required can then be calculated using the criterion set by Brooks and Di Chiro (1976) :

$$m = \frac{3 \pi n}{5}$$

- With the required density resolution and the established number of beams per view and number of views, Eq. 12 for the density resolution can be used to calculate the photon counting rate for a chosen sampling time.
- The required source strength can then be calculated using Eq. 15. The detection efficiency required here is best obtained by actual measurement using a calibrated source. The solid angle that is also required in this equation depends on the source-detector geometry and the collimator design and can be calculated using an appropriate expression provided by Tsoufanidis (1983).

- If certain design specifications are not met some parameters must be relaxed and iteration through the above procedure is called for.

8 Application of Tomography in Engineering Research

Although Computed Tomography (CT) has found extensive application in the medical field its use for engineering applications has been relatively recent and limited in range. It has been used mostly for nondestructive testing of materials, such as manufactured parts like turbine blades in the aerospace industry (Azevedo et al., 1993). A few cases, in which either tomography in its original form or its principles in combination with traditional measurement methods, appear in the process engineering research literature and are briefly discussed below.

Yule et al. (1981) combined the measurements from a light scattering technique with the tomographic reconstruction process for the measurement of droplet size and concentration in an axisymmetric spray produced by a twin-fluid atomizer. A HeNe laser beam is passed through the spray and the forward scattered light is collected by a Fourier transform lens arrangement. Particles of the same diameter produce the same radial scattered light intensity which is measured by a photodetector. The scattered light that is measured is effectively a line integral along the laser beam traversing different paths through the spray. The use of Fraunhofer diffraction theory, in combination with a tomographic reconstruction process, provides a two dimensional distribution of particle sizes and concentrations in a plane across the spray. A similar approach has been used by Liu et al. (1989) who applied tomographic reconstruction methods to the speckle photographic measurements of an asymmetric flow field with variable fluid density. Hertz (1985) used a Mach-Zehnder interferometer for recording projections of the index of refraction in a two dimensional flame from eight different directions. The projections are used to reconstruct the 2-D distribution of the refractive index, and a relationship is then used for obtaining the temperature distribution from the refractive index distribution. The integral measurements through a turbulent Helium jet were obtained by Watt and Vest (1990) using pulsed, phase-shifting, holographic interferometry. Multiangular viewing of the holographic interferograms provided the data for using tomographic reconstruction of the jet's concentration field.

All the above studies primarily used the tomographic reconstruction process for the line integrals measured using optical techniques. There are a few studies on the application of CT for the characterization of flow through porous media. Hicks et al. (1990) used a commercial X-ray CT scanner for studying the heterogeneities of carbonate cores with the objective of targetting the bypassed oil in carbonate oil reservoirs for improved oil recovery.

The axis of the scanner was reoriented from its original design to make the scan plane horizontal. Porosity and residual oil saturation distributions were of interest in this study. A similar study of core analysis for determining the saturation and distribution of fluids using a commercial X-ray CT scanner was made by Coles et al. (1991) at Mobil's R & D center in Dallas. Jasti et al. (1990) used a cone-shaped diverging X-ray beam along with a two dimensional X-ray detector to directly obtain a three dimensional reconstruction of the flow through porous media. Their system consists of an X-ray tube whose focal spot size is in the range of 1-5 micrometers. The accelerating potential used is 60 kV and the two dimensional transmission image of the object is captured by a two dimensional X-ray detector. Instead of the source and the detector arrangement rotating around the object to be imaged, the object is rotated about its own axis. This arrangement would be suitable to use for imaging static systems and where it is convenient to do so, which is often not the case.

Reported research studies in the literature focusing on the use of CT for holdup or concentration distribution of phases in chemical reactors such as bubble columns and fluidized beds are far fewer. The ones that have been reported were most often concerned with demonstrating the feasibility of using CT for this purpose. In addition, different kinds of tomography have been used in these studies.

Hau and Banerjee (1981) applied a tomographic reconstruction of two sets of mutually perpendicular scans obtained from a densitometer for a horizontal two phase flow. Their equipment consisted of a 100 mCi Pu 238 source, and a sodium iodide scintillation detector. The source-detector arrangement is mounted on a traversing mechanism such that the attenuation measurements could be scanned along vertical and horizontal chords. Seven such chordal measurements in the vertical and horizontal direction, making up a total of 14, were used to reconstruct the mixture density distribution on a 7×7 matrix. The algorithm for reconstruction was based on the Algebraic Reconstruction Technique (ART).

At the Idaho National Engineering Laboratory Fincke et al. (1980) used tomography to determine the time averaged density and its distribution in horizontal multiphase flows. Unlike the study mentioned above the hardware that was designed was truly a tomographic scanner. The system had 9 detectors arranged in an arc. The source used was a 0.5 Ci Americium - 243 with a 60 keV gamma as the principal photopeak. The source is collimated into a fan beam with a subtended angle of 32° . The assembly of source and detector array rotates about the pipe center line on ball bearing assemblies. The reconstruction of the density distribution is based on the Algebraic Reconstruction Technique (ART). The test section was three inches in diameter. Based on the gradients in density distribution they were able to differentiate between flow regimes ranging from stratified flow to annular flow.

De Vuono et al. (1980) carried out a parametric analysis for arriving at an optimum design of a CT scanner for two phase flow studies. This paper serves as an excellent starting point for the design of a CT system. The parametric analysis allows one to arrive at design parameters based on the requirements set for the spatial and density resolution, the size of the test section to be scanned along with constraints on the maximum available count rate (source strength) and the allowable scan time (i.e., the desired temporal resolution). The analysis has been made with reference to the fourth generation scanning configuration wherein there is a large number of detectors all around the test section and it is only the source of radiation that rotates on a circle between the detectors and the test section. However, some of the principles can be well utilized for the design of systems in the third generation configuration as well.

The application of gamma ray tomography for voidage measurements in fluidized beds has been demonstrated by Seville et al. (1986). The scanning system that was developed for that purpose was simple consisting of a 100 mCi Americium - 243 source and a single collimated NaI detector. The source and the detector were aligned using an optical bench. The fluidized bed was mounted on a rotating table so that it can be moved linearly with respect to the beam for obtaining measurements along different chords, and also rotated about its axis to obtain the measurements at different angular orientations. The test section was 14.6 cm in diameter and the spatial interval for the chordal measurements was 5 mm. The chordal measurements were obtained at 30 different angular positions at intervals of 6°. The total time for data collection for scanning one section was 6 to 7.5 hours. Because of the simplicity of the system's hardware, and the consequent long scanning times, an extensive study was not undertaken. The objective of the study appeared to be the demonstration of the feasibility of using CT for voidage measurements in fluidized beds. The CT scans of the grid region of the bed were used to compare the experimentally determined jet entrance length with theoretical predictions. An improved version of the scanner from the same group is reported by Simons et al. (1993). The new system had six Gadolinium-153 sources with corresponding six collimated CsI scintillation detectors. The assembly was mounted on a fixed rotation stage which had a central hole of 100 mm in diameter. The test section had to be lowered or raised through the scanning assembly so that different sections of the flow can be scanned. Each view consisted of a lateral translation in steps of 1.0 mm and each scan consisted of several views obtained by rotating the scanning assembly through 180° in steps of 1.5°. The reconstruction was done on a matrix of pixels 1 mm × 1 mm and the total scanning time was 3 to 4 hours. The scanner was used to study the differences in behavior of a spouted fluidized bed with dry and sticky particles in terms of the penetration of the inlet jet as well as the voidage profiles. This system has also been used by Ashrafi and Tuzun

(1993) for studying the granular flow of solids in a model hopper rig. The scanning time for each section is reported to have been reduced to 90 seconds. Contrary to the earlier system, in the refined system the scanning assembly rotates around the test section. The maximum size of the test section that could be scanned is 100 mm and the Filtered-Backprojection algorithm is reportedly used for image reconstruction. The cross-sectional profiles of solids fraction at different heights, as well as the plane mean values of void fraction, were obtained in both the cylindrical and conical sections of the hopper.

Banholzer et al. (1987) conducted a feasibility study for direct imaging of time averaged flow patterns in a model fluidized bed reactor using X-ray tomography. Essentially, a model fluidized bed (150 mm long, and 43 mm inside diameter) containing powdered coal was scanned using a medical CT scanner under a range of experimental conditions. The scanner made use of a 88-kW X-ray tube and an array of 517 gas filled X-ray detectors on the opposite side. The X-ray beam was collimated to a 1500 μm thick fan beam with an included angle of 30 degrees. The system was capable of scanning a section in 9 seconds. A spatial resolution of 1.5 mm and a density resolution of better than 30 kg/m^3 were achieved. No mention is made about the algorithm used for image reconstruction. Considering that the system used was a medical scanner the algorithm was probably the convolution-backprojection method.

Lutran et al. (1991) used a medical CT scanner for visualizing the liquid distribution in trickle beds with a quiescent gaseous phase. The test section was square, with a side of 7.3 cm and a height of only 30.48 cm, so that it was convenient to use a medical scanner and image the longitudinal sections of the bed. As in some of the earlier studies it appears that the dimensions of the test section in which the flow was studied were dictated by the largest scannable section (patient) by the scanner. Again since the system was a commercial scanner nothing was discussed about the hardware and the software for image reconstruction. The system was used to study the effects of liquid flow rate, prewetting, particle size, inlet configuration, surface tension and flow history on the flow pattern in the packed bed.

Kantzas (1994) used a EMI 7070 commercial X-ray CT scanner for obtaining the holdup distribution in fluidized and trickle beds. The scanner is of the fourth generation type and being a medical scanner it was modified to perform scans in both the horizontal and vertical direction. The system is capable of completing a scan for one section in 3 seconds. Spatial resolution of 0.4 cm $\times$ 0.4 cm is claimed. No mention is made about the reconstruction procedures. The fluidized bed studied was a glass bead - nitrogen system in a column of 10.0 cm in diameter. The gas was introduced in to the bed by a distributor plate with a long orifice in the center. A series of images as a function of time and position have been presented. The scans over the orifice tip showed the formation of a jet and a thin high-density ring surrounding the expanding jet corresponding to the high concentration of solids

around the jet. The trickle bed used in the study was a glass bead - nitrogen - water system in a glass column of 0.045 m diameter and 0.45 m length. The holdup of the liquid and gas phase under three phase conditions was calculated based on the scans made of the dry bed, a liquid saturated bed and the use of relativity principles.

X-ray tomography was used by Toye et al. (1994) for imaging the gas-liquid-solid distribution in trickling filters. The system consists of a point source X-ray generator that produces a fan beam with an included angle of 40° . The X-ray energy could be varied from 0 to 160 kV. The detector used was a linear array of 1024 photodiodes, so that effectively there were 1024 projections within the fan beam. The bed scanned had a diameter of 0.6 m and was 2m in height. A Fourier based algorithm for reconstruction was adopted. The reconstruction was done on a matrix of 1024×1024 pixels. The liquid holdup in the bed is claimed to be detected inspite of the low liquid film thickness around the packed solids.

9 Experimental Results for Void Fraction Distribution in a Bubble Column

We end our discussion of the research applications of tomography by presenting here some results on the void fraction distribution in bubble columns that were obtained using the CT scanner in our laboratory. Comparison of the void fraction results obtained using the CT scanner with results in the literature and with the data obtained using other techniques are presented in Kumar et al. (1995), and Kumar (1994). In this section the results for the effect of operating conditions on the void fraction and its distribution in bubble columns are discussed. Experiments were performed in bubble columns of five different diameters (0.102, 0.14, 0.19, 0.26 and 0.30 m) using air and mainly tap water as the gas and liquid phase, respectively. Four superficial gas velocities - 0.02 m/s, 0.05 m/s, 0.08 m/s and 0.12 m/s - were used for most of the columns. These velocities cover all the flow regimes from bubble to churn turbulent in all the columns. For all the column sizes the experiments were conducted with a static liquid height to diameter ratio of at least 5. All the runs were made with zero liquid superficial velocity. The data was obtained mainly in columns fitted with a perforated plate distributor. The distributors were made out of 0.0032 m thick aluminum plates. The open area of the distributors ranged from 0.05 to 0.23 %. The characteristics of the hole patterns and their sizes for the different columns can be found in Kumar (1994). To evaluate the effects of gas distribution, the flow in the 0.19 m diameter bubble column was imaged with two other types of gas distributors in addition to the perforated plate. These were a simple cone and a single bubble cap riser. For most of the runs the scans were performed at five different elevations above the distributor for capturing the evolution

of void distribution with flow development. Most of the results reported here are the void fraction profiles that have been averaged over those sections of the flow for which the end (i.e., entry and disengagement sections of the flow) effects are negligible.

Effect of Column Diameter

The effect of column diameter on the void fraction distribution is shown in Fig. 11 (a) and (b) for superficial gas velocities corresponding to flow in the bubbly and churn turbulent flow regimes. The void profiles are from scans of the columns at a section where end effects are negligible. At the low gas flow rate ($U_g = 0.2 \text{ m/s}$) it is evident that there is some influence of the column diameter on the void fraction although there appears to be no specific trend. In churn turbulent flow at the gas flow rate corresponding to $U_g = 0.08 \text{ m/s}$

Figure 11: Effect of column diameter; (a) $U_g = 0.02 \text{ m/s}$, (b) $U_g = 0.08 \text{ m/s}$

there is a continuous increase in the void fraction with column diameter. The integral area under the curves were computed to evaluate the cross-sectional mean void fraction. These are tabulated in Table 4. At the low gas velocity the cross-sectional mean void fraction decreases initially with the column diameter and then increases again. At the higher gas velocity the holdup values continuously increase with the column diameter, although this increase tapers off gradually. This observation is in line with the observation made in the

literature that the overall gas holdup is unaffected by the column diameter provided it is greater than 0.15 m.

Table 4: Cross-Sectional mean void fraction as a function of column diameter

Column i.d. - m	X-Sect. Mean Void Fraction	
	$U_g = 0.02 \text{ m/s}$	$U_g = 0.08 \text{ m/s}$
0.10	0.106	0.191
0.14	0.094	0.209
0.19	0.075	0.225
0.26	0.095	0.234
0.30	0.104	0.238

Effect of Superficial Gas Velocity

The effect of superficial gas velocity on the void fraction distribution is illustrated in two of the columns studied. Fig. 12 (a) and (b) correspond to the void fraction distributions obtained in the 0.10 m and 0.26 m diameter columns as a function of superficial gas velocity. The data correspond to scans at one fixed axial location that is well away from entrance or free surface effects. In general, an increase in the gas velocity leads to an increase in the magnitude of the local void fraction at all column radii except at regions close to the wall. The magnitude of this increase is much larger at the lower velocities corresponding to the bubbly and transition flow regimes. At the higher velocities (churn turbulent flow) the increase is relatively small. The holdup profile changes from a flatter distribution to a more parabolic one with increase in the superficial gas velocity.

Effect of Distributor Type

The effect of the type of distributor used on the void fraction distribution was studied in the 0.19 m diameter column. Three different kinds of distributors were used. The first of these was a perforated plate having 156 holes on a square pitch of 1.25 cm leading to an open area of 0.1 %. The second was a cone distributor and the third distributor used was a bubble cap. Their geometrical characteristics are illustrated in Fig. 13.

The cross-sectional distribution of the void fraction distribution shown in Fig. 14 clearly shows the differences resulting from the distributors. It is seen that the perforated plate results in a uniform distribution of the gas and this gets reflected in the gradual variation in the colors for the void fraction from the column center to the wall. For the cone and

Figure 12: Effect of superficial gas velocity; (a) Col. i.d. = 0.10 m, (b) Col. i.d. = 0.26 m

Figure 13: Characteristics of (a) Bubble cap, (b) Cone distributor

Figure 14: Void fraction distribution from three distributors; Col. i.d. = 0.19 m; $z = 0.83$ m; $U_g = 0.04$ m/s; Distributor : (a) Bubble Cap, (b) Cone, (c) Perforated plate

the bubble cap distributors the gas moves up the column as large bubbles in a region close to the column center. The peripheral regions are almost unaerated and this is reflected as an annulus of light shades in the cross-sectional image. At the higher gas velocities these differences get minimized owing to the breakup of the large bubbles due to the higher intensity of turbulence generated at these flow rates.

It is common in academic research to use a sintered plate distributor. The comparison of such a distributor and a perforated plate distributor was studied in the 0.10 m diameter column. The liquid phase used was a mixture of isopropanol and water mixed in equal volumes. The comparison between the void profiles resulting from the two kinds of distributors are shown in Fig. 15. This mixture resulted in very fine bubbles and at high velocities also led to excessive foaming especially with the sintered plate distributor. The magnitude of the holdup generated by the sintered plate is larger than that of the perforated plate and this difference increases with increase in gas velocity. At $U_g = 0.8$ m/s the foaming tendency with the sintered plate distributor is very well discerned by the CT scanner.

Effect of Liquid Properties

The effect of using highly purified and deionized water against regular tap water was studied in the 0.14 m diameter column. The deionized water was obtained from a compact

Figure 15: Void fraction distribution from sintered plate and perforated plate distributor; Col. i.d. = 0.10 m; $z = 1.0$ m; (a1, a2) $U_g = 0.04$ m/s; (b1,b2) $U_g = 0.08$ m/s; (a1,b1) perforated plate; (a2,b2) sintered plate

Milli-Q Plus water purification system that produces Type I reagent-grade water with a resistivity of 18 megohm-cm. The column, the distributor and the plenum were all washed with the same water before the actual runs. The void fraction distribution obtained from the CT scans of the column at an axial distance of 0.6 m above the distributor are shown in Fig. 16 for two different superficial gas velocities. The magnitude of the void fraction with the deionized water is always lower than that obtained with regular tap water. The bubble sizes observed in the column with deionized water were much larger and consequently, the holdup in the former is lower. These observations are consistent with the results of Anderson and Quinn (1978) who contend that the pure water promotes coalescence of the bubbles.

The effect of liquid physical properties was also studied by comparing the void distributions obtained with tap water and a mixture of tap water and isopropanol mixed in equal volumes. The isopropanol-water mixture had a viscosity of 0.00278 kg/m-s at 26°C, a surface tension of 28.2×10^{-7} N/m and a density of 917 kg/m^3 . The bubble sizes observed in the mixture were small and of the order of 1 to 2 mm. This leads to extremely high values of the void fraction. The comparison between the two cases is depicted in Fig. 17.

Figure 16: Effect of liquid properties - tap water and deionized water ; Col. i.d. = 0.14m, (a) $U_g = 0.038$ m/s, (b) $U_g = 0.169$ m/s.

10 Process Applications of Tomography

Use of tomography to study industrial scale reactors has not been reported to the best of our knowledge. This is primarily because of the complexity involved in setting up a CT system around an installed reactor. Space constraints and the existence of other structures in the vicinity such as flanges, piping, platforms, other auxiliary equipment and structures are the impediments for accomplishing a complete CT scan. In addition, the cost of obtaining the data for a complete scan is often prohibitive and its justification is considered difficult. However, a popular diagnostic tool in the chemical and process industry, executed by a number of small specialized companies, is commonly referred to as "gamma scanning". In its simplest form it was originally conceived as a diagnostic tool in the chemical and process industry. In its simplest form it was originally conceived by Du Pont in the 1960s (Severance, 1981) and has been subsequently improved and widely used (Severance, 1985; White, 1987; Harrison, 1990). In particular this technique has been extensively used for trouble shooting on distillation columns. The information obtained is used to detect the dislocation of trays, extent and location of tray flooding, liquid levels on aerated trays, location and characteristics of foaming, entrainment conditions etc. Essentially the attenuation of radiation of a single beam of radiation (probably along the centerline) is obtained as a function of axial position along the column. The signature profiles for an empty column, a normally operating column,

Figure 17: Effect of liquid properties - water and water-isopropanol mixture ; Col. i.d. = 0.10 m, (a) $U_g = 0.02 \text{ m/s}$, (b) $U_g = 0.08 \text{ m/s}$.

a flooded column etc. are established and then compared with the actual scan and used for problem diagnosis. Thus, the scan profiles are used as a visual representation of the hydraulic condition of the distillation column.

These simpler radiation techniques are finding great patronage by the chemical and process industry in the U.S. judging by the proliferation of companies that offer to provide such measurements as service. In recent years these companies provide what is known as two angle gamma scanning, which is the same as gamma ray densitometry. A gamma ray source on one side of the reactor and a radiation detector on the other side are mounted and a series of measurements for the attenuation of a narrow beam of radiation along several chords are obtained. This is then repeated at right angles to the first set of measurements by reorienting the source-detector arrangement. By identifying those paths in each set of measurements along which the attenuation is either maximum or minimum, it is claimed that the location and extent of the problem areas can be determined. To demonstrate that this is not necessarily true, we consider a reactor in which the cross-sectional distribution of gas holdup is represented (for illustrative purposes) by a 4×4 matrix of numbers as indicated in Fig. 18. The two angle scans are simulated by assuming that the initial number of photons is 10,000 and that each pixel in the matrix has unit length. Using the Beer-Lambert's law (assuming an ideal situation) the measured count rates for four individual beams at two positions that are 90 degrees apart are shown in Fig. 18. If the above described procedure is applied to

the two scans one would conclude that the highest holdup of the less dense phase (gas) lies at the intersection of the beams with the highest count rates and the lowest holdup at the intersection of beams with the lowest count rates. By using this argument in this simulated case the conclusion would be that the lowest holdup of the less dense phase (gas) should be in the pixel at the intersection of the fourth beam from left in the vertical direction and the third beam from the top in the horizontal direction which has a holdup of 0.2. Actually, the

Figure 18: Gamma scan at two right angles

lowest holdup of 0.1 lies in another pixel that is not traversed by these beams. Similarly, the highest holdup using this interpretation would be given by the pixel at the intersection of the second beam from the left in the vertical direction and the first beam from the top in the horizontal direction. This pixel has a holdup of 0.3 while the maximum holdup in the distribution is 0.9.

The reason for the failure of the above described procedure to identify regions of highest or lowest holdups lies in having fewer equations than unknowns. Mathematically, one would require at least 16 independent attenuation measurements in order to determine the 16 unknown holdups (one in each cell) so that one has to obtain the measurements corresponding to at least two other angular orientations of the source-detector arrangement with respect to the reactor. Even with 16 measurements the distribution cannot be uniquely determined, since it is always possible to find a suitable combinations of numbers to satisfy the constraints set by the attenuation measurements. Theoretically speaking, for an accurate reconstruction an infinite number of measurements are required, which of course is not practically feasible.

However, the above example demonstrates that a set of two measurements at right angles lead to misleading conclusions, and one would require a reasonable number of such sets of measurements to make a diagnosis.

For industrial systems it is convenient and less expensive to obtain a few chordal measurements of the attenuation through the test section. Unfortunately, it is often forgotten that a single line averaged holdup, even if it is obtained across the centerline of the column is not representative of the cross sectional mean. The line averaged holdups along several chordal positions can, however, be used to obtain a cross-sectional mean provided that one assumes that the holdup distribution is axisymmetric. If such an assumption can be made, the radial variation of the holdup and, hence, the cross-sectional mean can be obtained by making use of the Abel integral and its inversion.

If $f(r, R)$ is a function of radial position that is nonzero only within a circle of radius R , then its Abel transform is

$$\phi(x, R) = 2 \int_0^{\sqrt{R^2 - x^2}} f\left(\sqrt{x^2 + y^2}, R\right) dy = 2 \int_x^R \frac{f(r, R) r}{\sqrt{r^2 - x^2}} dr \quad (19)$$

The above is merely the line integral along the ray in the y direction at the position x in the x - y coordinate system. The inversion expressing f in terms of ϕ is

$$f(r, R) = -\frac{1}{\pi} \int_r^R \frac{d\phi/dx}{\sqrt{x^2 - r^2}} dx \quad (20)$$

For our case, the quantity $\phi(x, R)$ corresponds to the quantity $\ln(I_0/I)$ divided by the corresponding chordal length. Many different numerical approaches have been suggested for the implementation of the Abel inversion (Bockasten, 1961, W. L. Barr, 1962, Dong and Kearney, 1991). To illustrate that the centerline averaged holdup is an overestimate of the cross-sectional mean, and that the Abel inversion provides a radial distribution that leads to the correct cross-sectional mean, the following simulation has been made. An axisymmetric distribution of the holdup is assumed in an air-water bubble column of 19.05 cm in diameter. The assumed radial distribution has the functional form (Kumar, 1994)

$$\epsilon(\xi) = \bar{\epsilon} \frac{m+2}{m} (1 - c\xi^m) \quad (21)$$

where $\bar{\epsilon}$ is the cross-sectional mean holdup, m is the power law exponent and c is a constant that provides for non-zero holdup at the wall of the column. These parameters were obtained from the experimentally determined void fraction distributions using the CT scanner at CREL. The value of the power law exponent is high for a flat holdup distribution (corresponding to bubbly flow) and decreases for the more parabolic profile that is observed in

Figure 19: Comparison of assumed distribution, chordal averages and Abel inversion, (a) Bubbly flow, (b) Churn turbulent flow

churn turbulent regime. For a given holdup distribution the line integrals corresponding to the quantity $\int (\mu_{\text{air}} \epsilon + \mu_{\text{water}} (1 - \epsilon)) dl$ are computed. The limits of integration depend on the position of the chord. The negative exponential of this quantity would correspond to the ratio I/I_0 that is measured in densitometry (as well as CT). Shown in Figures 19 (a) and (b) are the assumed symmetric holdup distributions (similar to experimentally determined holdup profiles in the two flow regimes), and the chordal average holdups that are obtained from the simulated line integrals for two values of m corresponding to bubbly and churn turbulent regimes, respectively. Also shown as a horizontal line for comparison is the cross-sectional mean. The chordal averaged centerline holdup is always higher than the cross-sectional mean. Using the entire set of chordal measurements, the Abel inversion pro-

vides a radial distribution that is the same (within numerical error) as the assumed (original) axisymmetric distribution. Abel inversion yields reliable results only when the distribution is axisymmetric. For industrial systems the current measurement practice can be modified to provide the chordal average measurements at two positions at right angles to each other. An assessment can then be made whether the assumption of axisymmetry is appropriate and if so a cross-sectional mean using Abel inversion can be obtained.

11 Recommendations for Improvements in Gamma-Ray Scanning of the AFDU Reactor at LaPorte

We conclude this report by providing guidelines for enhancing the measurements of holdup on the AFDU reactor at LaPorte using the nuclear density gauge. At present the instrumentation is being used for the measurement of only the chordal average holdup along the centerline of the reactor. It is recommended that for a given cross section the measurements be obtained along several such chordal positions at a minimum of two angular orientations (90° apart) with respect to the reactor. For the reactor of 18 inches in diameter it would be ideal to have a minimum of 12 chordal measurements across the section. This we believe is the least that has to be done and can be accomplished with minimal effort. Since the system is actually a three phase system it is desirable to resolve the concentration distribution of the three phases individually, and for this one has to resort to dual energy scanning. To accomplish this a gamma ray source with emissions at an energy different from that of the existing Cs-137 (0.66 MeV) source is required. Two possible options are Americium-241 (0.0595 MeV) and Cobalt-60 (1.17 MeV & 1.33 MeV). Although, the ideal choice for the second source is Am-241, the attenuation at this low energy of the source in a relatively large diameter system is high, and it becomes necessary to collect the data over long periods of time in order to obtain statistically significant photon count rates. Thus, the higher energy level emissions from Co-60 would appear to be a better choice. However, the attenuation coefficients of typical materials at the energy levels of Cs-137 and Co-60 are not vastly different to enable a clear resolution of the individual phases. This is because the calculated values of the phase holdups are very sensitive to small errors in the count rate measurements. Table 5 lists the linear attenuation coefficients of air, water and glass at four energy levels. If Co-60 is used as the second source, then it is better to gate in on the 1.33 MeV photopeak since that provides a wider difference in the attenuation coefficients with respect to the energy level of Cs-137. This of course requires additional hardware in the signal processing train to be able to differentiate between the photons at the two energy levels.

Finally we provide a design for what we call as the "Poor Man's Tomograph". The system

Table 5: Linear Attenuation Coefficient of some materials as a function of energy

Material	$\mu - cm^{-1}$ at 0.06 MeV	$\mu - cm^{-1}$ at 0.66 MeV	$\mu - cm^{-1}$ at 1.17 MeV	$\mu - cm^{-1}$ at 1.33 MeV
Air	2.14E-4	9.29E-5	7.67E-5	6.81E-5
Water	0.197	0.0857	0.0662	0.0619
Glass	0.5625	0.1942	0.1485	0.1387

is referred to by this title, since having a sophisticated CT system capable of providing fine spatial resolution is expensive and not practical for use on an industrial scale reactor. Thus, the system that we propose to be implemented for the reactor at LaPorte is capable of a spatial resolution of $3.0 \text{ cm} \times 3.0 \text{ cm}$, and does not require too long a period of time for scanning (considering the size of the reactor) and also is relatively simple in construction.

The system proposed here is novel in the sense that it combines the fan beam scanning configuration with the parallel beam scanning configuration. A schematic of the proposed scanning configuration is shown in Fig. 20. The arrangement consists of a source with the emissions collimated to a fan-beam with an included angle of about 20° and an array of three detectors whose centerlines are 5° apart. This assembly is designed to translate across the section for a given angular orientation with respect to the reactor. The idea here is that as the assembly traverses linearly across the section each detector is obtaining chordal measurements in separate views that are 5° apart. Once a linear scan is complete the whole assembly is rotated by 15° and the process is repeated until views over 180° have been obtained.

We follow the methodology for the design of a CT scanner set up in Section 7. The design is for a column of 61.0 cm (2 feet) inner diameter with a required spatial resolution of $3.0 \text{ cm} \times 3.0 \text{ cm}$. The preset parameters are :

1. $d_i = 61.0 \text{ cm}$ (column inner diameter)
2. $d_o = 63.5 \text{ cm}$ (column outer diameter)
3. $\Delta x = 3.0 \text{ cm}$ (spatial resolution)
4. $\sigma_\rho = 0.1 \text{ g/cm}^3$ (density resolution)
5. $S \leq 5 Ci$
6. $N = 25 - 50 \text{ counts / sec}$

Figure 20: Schematic of the proposed scanning configuration

The assumptions are :

1. 180° scan
2. ϵ - detecting efficiency = 0.75
3. Energy level of photons : 0.66 MeV (Cs-137 source)
4. A maximum of 50 % solids loading with attenuation characteristics similar to glass.

For the required spatial resolution the collimators are designed to have rectangular apertures $3.0 \text{ cm} \times 1.5 \text{ cm}$. Using Eq. 16 the solid angle Ω is calculated as 0.0474. The column walls are assumed to be 0.5 inches thick and made of steel ($\rho\mu = 0.5678 \text{ cm}^{-1}$ at 0.66 MeV). With 50% solids loading the integral of the product μl for all the material that the beam encounters along the center line of the reactor is 18.74. Using Eq. 15 the counting time required per beam (for the chosen count rate) with a 5 Curie source is calculated to be 40 seconds.

For a column of 2 feet in diameter with a required spatial resolution of 3.0 cm the number of chordal measurements required in one linear scan would be approximately 20 (number of

beams per view). However, from our experience with the CT measurements in our laboratory it seems appropriate to obtain half the above required number of chordal measurements and obtain the required number of beams by interpolating in between two measured beams. This is a reasonable method to adopt and aids in reducing the scanning time. The scanning time per view is therefore 40 seconds $\times$ 10 beams. The number of views required is calculated as 36. In the proposed methodology of scanning at any given time the data is being acquired for three views simultaneously. Hence, the required number of angular increments is 12, so that the total scanning time works out to be approximately 86 minutes.

The hardware for the support structure and the positioning mechanism can be made relatively simple and easy to install around a commercial reactor. Implementing such a system would go a long way in providing experimental information that definitely would serve in enhancing our understanding of the fluid dynamics of the system.

Implementing the dual energy scanning system with Co-60 as the additional source should be preceded by a preliminary study for evaluating if energy level differences between the emissions from Co-60 and Cs-137 is adequate for differentiating the three individual phases.

12 Nomenclature

A	absorptance of a medium
A_a	effective detector area
A_d	total detector area
d_a	actual detector aperture width
d_{eff}	effective detector aperture width
d_o	outer diameter of pipe
d_i	inner diameter of pipe
I	intensity of transmitted radiation
I_o	initial intensity of radiation
I_d	number detected photons
I_e	number emitted photons
l	path length of a beam of radiation through an object
L	total path length of radiation in a mixture of phases
m	total number of views per scan
M	magnification factor
n	number of beams or projections in a view
N	average number of photons per beam number of observations or samples
P	projection function in equation (4)

r	photon count rate - photons/sec
S_o	source strength - photons/sec
s	focal spot width of the source
T	transmittance, ratio of I to I_o
U_g	gas superficial velocity, m/s

Subscripts

w	water
p	pipe

Greek Symbols

Δx	spatial resolution
ϵ	detection efficiency
μ	mass attenuation coefficient, cm^2/g
Ω	Solid angle
ρ	material density, g/cm^3
τ	photon counting time
σ_ρ	density resolution

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