Intercomparison of gamma ray scattering and transmission techniques for fluids interface level and density determination

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Abstract
This paper focuses on the immiscible fluid-fluid, fluid-air interface level detection and density determination by gamma scattering method and intercomparison with transmission (gammatography) technique. The gamma scattering NDE method utilizes scattered gamma radiation for the detection of interface level and density and the experimental set-up is an indigenously designed automated PC controlled gamma scattering scanning system. Gamma rays from $^{137}$Cs radioactive source scattered from the fluid columns in glass pipes are detected using an HPGe detector. A simple and straightforward reconstruction algorithm to reconstruct the densities of the objects under investigation is given. The Monte Carlo (MC) numerical simulation of the scattering phenomena is done using the MCNP code and the spectra are compared with experimental data. The density and fluid level interface resolution achievable in the case of gamma scattering method are higher compared to those obtained from transmission method. Overall these results are consistent and in line with each other.

Keywords: NDT-wide, gamma ray scattering, gammatography, fluid interface level, density

1. Introduction
The need for NDE techniques that require access only to the one side of any material or structure relatively thick to be inspected has drawn attention to x-ray or gamma backscatter as a desirable choice. Compton scattering measurements have been employed in the past for industrial applications, to detect inhomogeneity, voids and cracks at the interior of not accessible structures, or to determine density or density variations [1-4]. The same technique has been applied to the problem of identifying and detecting explosive material in airport luggage and buried land mines [5-7].

There are many situations where the fluid level has to be monitored or maintained continuously and although fluid monitoring technology has come of age in recent years, its level of sophistication varies widely across industries. Detection of levels and the decision according to that are required in the catalyst plants. Waste water treatment plants need to continually monitor various parameters, including water levels [8]. Ultrasonic, radar, florescence and capacitance based level measurements are some of the many methods that widely use for this purpose. No single means of fluid density and interface measurement technique is either ideal or suitable in all cases. There are major advantages and disadvantages of the fluid level and interface characterization technologies.

Gamma ray based measurement is a viable tool for the level monitoring of highly carcinogenic, toxic, explosive and pressurized fluids as it doesn’t require any physical contact with the fluids. Fluid level gauging based on this technique is very effective in fully enclosed vessels, high temperature vessels and high pressure vessels. Transmission technique requires a radioactive source either inside the fluid or outside the container and the detector on the opposite side of the source. For larger container size and higher fluid density, transmission technique results in fewer gamma rays reaching the detector due to higher absorption which limits the effectiveness of this technique in fluid density and interface measurements. The back scattering technique has the advantage of one sided source and detector arrangement enhancing reasonable...
counts at the detector even in dense fluids due to the scattering. Compton back scattering fluid level gauge is a reasonable technique for highly dangerous fluids when two sided access is restricted. The scattered signal provides a measure of the electron density $\rho_e$ of the material comprising the inspected volume. Any change in the scattered intensity indicates the change in fluid level, or change in the fluid density on the raster scanning. Like in the transmission, the back scattered mode can also function in both switch on/off and continuous manner. The former is used in determining whether the fluid is above or below a certain level by keeping the source and detector fixed, while the latter is used for continuous level investigation by the movement of source detector assembly. Collimated gamma rays are used in both transmission and back scattering geometry for the fluid level gauging [9]. Dual Modality Densitometry (DMD) measurement is useful for the measurement of Gas Volume Fraction (GVF) in oil/ gas/ water flows [10-12] and measurements of water salinity [13]. The responses of material both to photo electric absorption and the Compton scattering are utilized in this measurement mode by measuring the intensity of transmitted and scattered gamma radiation. Density measurements for solutions (miscible and immiscible) and slurries in pipelines are carried out on-line using this method [14]. The bulk density of slurries can be used for the calculation of solid weight fraction [15-16].

The present work focuses on the fluids interface level and density determination of immiscible fluid combinations of olive oil- glycerin, castor oil- glycerin, hexane- water enclosed in cylindrical glass tubes by gamma scattering and intercomparison of results obtained from gammatography technique. The PC controlled scattering scanning system has been successfully used to decide the polar to non polar fluid boundaries, fluid to air boundaries without any direct contact within the cylinder holding the fluid or positioning any device or apparatus within the pipe. A simple and straightforward reconstruction algorithm to reconstruct the densities of the objects under investigation and an unambiguous interpretation of the signal as a function of material density at any point of the thick object being inspected is described. In this method the density of the target need not be known and only the knowledge of the target material’s mass attenuation coefficients (composition) for the incident and scattered energies are enough to reconstruct the density of the each voxel of the specimen being studied. As the scattered intensity depends on the effective density and thickness of the sample within the voxel, the magnitude of density within the voxel are determined by iteration from the known values of mass attenuation coefficients and the geometrical parameters. The iterated densities and interface levels are compared with those values obtained from transmission technique. The Monte Carlo (MC) numerical simulation of the scattering phenomena is done using the MCNP code and the spectra are compared with experimental data.

2. Theory
Compton scattering is the interaction of photons with electrons. Thus scattered intensity, $I(P)$ carries information about the electron density and average chemical composition of the fluid. $I(P)$ is the overall effect of three stages as (1) attenuation of the incident energy along the path of source to scattering point, (2) scattering at the point towards the detector and (3) attenuation of the scattered energy along the path of scattering point to detector. The resulting equation from combining the three stages is:

$$I(P) = I_0 \exp \left( \frac{\mu(E_0)}{\rho} \rho x \left[ d\sigma(E_o,\Omega) \frac{d\Omega}{d\Omega} S(E_0,\theta,Z)d\Omega \rho_e(P)V \exp \left( \frac{\mu(E)}{\rho} \rho x \right) \right] \right)$$

(1)
where $I_0$ is the incident intensity, $\mu(E_0)/\rho$ is the mass attenuation co-efficient of the fluid for the incident energy, $\mu(E)/\rho$ is the mass attenuation co-efficient of the fluid for the scattered energy, $d\sigma(E,\theta)/d\Omega$ is the differential scattering cross section given by Klein-Nishina relation, $d\Omega$ is the solid angle subtended by the detector and its collimator, $V$ is the voxel volume and $\rho_e(P)$ is the electron density at scattering point $P$.

$$\rho_e = \rho N \frac{Z}{A}$$  \hspace{1cm} (2)

where $N$ is the Avogadro’s number, $Z$ is the atomic number and $A$ is the atomic weight. The scattered intensity varies with the fluid level and this is explained as follows. The complete intersection of voxel with the fluid level gives more intense scattered peak than at the boundary or interface. When the scattering point is fixed at the desired level, any change in the scattered count not within the statistical limit indicates a fluctuation in the fluid level. Other mode of scanning is by step wise movement of the voxel along the direction of fluid height, and observing the scattered count. The fluid level, boundary of mixture of immiscible fluids and their densities can be determined from the scattered counts. The accuracy of level estimate depends upon the voxel size. Finer collimation of source and detector reduces the voxel size which in turn demands more counting time to get the desired statistical accuracies. For a fixed source and detector positions and the collimator sizes, equation (1) reduces to:

$$I(P) = K \rho \exp \left[ \left( \frac{\mu(E_0)}{\rho} \right) \rho x \right] \exp \left[ \left( \frac{\mu(E)}{\rho} \right) \rho x \right].$$  \hspace{1cm} (3)

where,

$$K = I_0 \frac{d\sigma(E_0,\Omega)}{d\Omega} S(E_0,\theta,\Omega) d\Omega A \frac{N Z}{A}$$  \hspace{1cm} (4)

$K$ is a constant for a given geometrical setup. Equation (3) clearly establishes the relation of density of the scatterer with the scattered count. The assumptions that all the points within the voxel are scattered with equal probability and all these events are lumped into a single point validate equation (4) for the reconstruction of fluid density. The above assumptions also demand a reduced voxel size [17].

The information concerning the density of fluid is provided by the single scattered component of the detected radiation. Secondary scatter events occur when scattered photons from the primary interactions interact again before leaving the object. These multiple scatter components contribute a background signal which reduces sensitivity, accuracy, and prediction. The probability of a multiple interaction depends on the size of the interaction volume. Some attempts to solve the problem analytically have been made, which can be found from the literature [18-19], but must be considered to be very crude approximations, partly because they do not include an energy distribution. Multiple scattering can be evaluated with the Monte Carlo method. Many interesting results of Monte Carlo calculations have been reported, especially by the groups interested in the development of new devices for the measurement of the Compton profile [20-21]. The results reported show that the energy distribution of the multiple scattered photons is quite flat and that the contribution can be considered negligible when a light matrix and a small sample have been used. The solution to multiple scattering is to use high energy
resolution detector so that multiple scattering contribution can be separated and setting smaller energy window width $\Delta E$ around the Compton peak and is followed in the present investigation. In the idealised system the detector collimator can be expected to exclude most secondary scatter by reducing the voxel.

2.1 Attenuation Correction

The number of detected photons depends on the number of scattered photons, as well as on the attenuation all along the path within the material. The attenuation factor is calculated theoretically by employing the method described in the reference [22]. Prior knowledge of the composition of the object is required for this purpose and the object is simulated in MATLAB. The simulated image is divided into grids (pixels) and each pixel is assigned the value of the attenuation co-efficient of the corresponding point in the object for incident gamma energy. The incident gamma path is also simulated using the angle formed by incident ray to the normal of the object. The path length $dl$ in each pixel is obtained and multiplied by the corresponding pixel value ($\mu dl$) and the total incident attenuation correction is calculated by $\exp \left( \sum \mu \text{dl} \right)$ over the path length. The total scattered attenuation correction is also calculated in the same method by assigning the attenuation co-efficient corresponding to scattered energy as pixel value and by simulating the scattered path. The attenuation corrected scattered count is given by:

$$I_{\text{corr}} = I(P) \exp \left( \sum \mu dl \right) \exp \left( \sum \mu dl' \right) = K \rho$$

(5).

The corrected scattered count is having a direct proportional relation with the density. For calculating the attenuation function in the present case, standard density is used and this demands the uniformity of the material within the pixel apart from the assumptions stated already.

3. Experimental Procedure

The experimental set-up shown in Fig.1 is an automated PC controlled scattering scanning system consisting of CNC controlled 6-axis source - detector system and a 4-axis job positioning system. A well collimated and lead shielded radioactive source $^{137}$Cs of strength 155.4 GBq (4.2 Ci) and a 50% efficiency coaxial HPGe detector providing high resolution energy dispersive analysis of the scattered spectrum are mounted separately on the 6-axis source - detector sub assembly system. The HPGe detector consists of a crystal of size 0.066 m × 0.066 m surrounded and sealed by an aluminum layer. The source and detector can be rotated and translated in lateral and vertical directions and the positional accuracy for lateral and vertical travel stages is ± 50

![Figure 1. Experimental set-up](image.png)
microns. The motion of the job positioning system is achieved by 4 servo motors, three motors used to move the specimen in three perpendicular Cartesian coordinate system and the fourth servo motor is used to rotate the specimen. The positional accuracy of 4-axis in three perpendicular directions is ± 10 microns. The positional accuracy for θ rotary stages for 4-axis and 6-axis systems is ± 0.25 degree. The servo motors are controlled by Galil’s DMC 2040 motion controller programmed with Galil commands and the commands are communicated from PC via high speed RS 232 port. The gamma spectroscopic data acquisition is done by FAST COM 8K Multi Channel Analyzer (MCA) PC Add-on card. The motion of 4-axis CNC controlled job position system and MCA data acquisition are fully automated using VB based windows application program.

The combinations of polar and non polar fluids like glycerin- olive oil, glycerin- castor oil and water- hexane are chosen for fluid level and density measurements. A cylindrical glass container of diameter 0.016 m and height 0.15 m, containing the fluid combination is placed on the job positioning system’s specimen disk located at a distance of 0.934 m from the source and 0.521 m from the detector and the scattering angle is 109 degree. The same combinations of fluids enclosed in SS cylindrical container of 0.025 m in diameter and thickness 0.002 mm and PVC cylindrical container of 0.025 m in diameter and 0.0015 m thickness are also scanned individually. The diameters of the source and detector collimators are 0.0055m and 0.007m respectively and the voxel size is $27.5 \times 10^{-6}$ m$^3$. The incident and scattered photon energies are 661.6 and 242 keV respectively. The experiments are carried out by vertical and horizontal scanning in steps of 0.002 m. Each voxel is scanned for adequate time to get enough counts for achieving good statistical accuracy. The scattered intensity from the specified voxel of the fluid is detected and the Pulse Height Spectra (PHS) with channel width of 0.74 keV is recorded. The background PHS for the same duration is also collected and subtracted from the scattered intensity. The transmission or gammatography experiments are carried out using the same PC controlled scanning system in a narrow beam, good geometry set-up (0.0055m collimators for both source and detector) using a 0.159 GBq (4.3 mCi $^{137}$Cs) to estimate polar to non polar fluid boundaries, fluid to air boundaries and densities. The detector employed in transmission experiments is the same HPGe detector used for scattering.

4. Monte Carlo calculations

The MC simulations have been done which takes into account the detailed characteristics of the source, detector and the scatterer, in calculating the PHS. The MCNP4C [23] radiation transport code is applied to perform the calculations in this work and it is a general purpose, three-dimensional general geometry, time-dependent code, which is used to calculate coupled neutron-photon-electron transport in bulk media. In MCNP simulations, each particle (photon) is tracked from creation until termination with all interactions based on physics models and cross-sections, and all decisions (location of interaction, scattering angle, etc.) are based on pseudo-random numbers. Usually, the results of a simulation are normalized per starting source photon. New source photons are randomly created until a preset number of histories are tracked and the simulation is ended. The desired result in the simulation component of this study is a PHS since it produces the distribution of the energy deposited in a “cell”, i.e. the gamma ray energy spectrum in a physical model of a detector.

The $^{137}$Cs radioactive source capsule of activity 155.4 GBq deposited inside stainless steel capsule and the HPGe detector is modeled with the surrounding lead shielding and a
0.0055m beam collimator for source and 0.007m for detector. The HPGe detector consists of a crystal of size 0.066 m × 0.066 m surrounded and sealed by an aluminum layer 0.002 m thick in front and 0.001 m on sides. A glass container of 0.15m height, inner radius 0.006m and outer radius 0.008m containing the fluids and their distances from the collimator edge of source and detector set-up, the scattering angle and the sizes of the source and detector collimators are incorporated in the modeling. The simulated pulse height spectra contain 28 bins, each with a width of 3.615 keV width and the photon energies ranged from 198 to 303 keV. The measured PHS is rebinned to the same energy grid as the MCNP calculation for the purpose of comparison. For the pulse-height (energy-deposition) estimates used in this study, the source biasing represents the only feasible method to improve computational efficiency. Herewith, the directional (source) biasing function is used to make the source emitting particles to move as a fine beam towards the object. Each simulation is run with 2.1 billion source particles. This number of source particles is chosen because the absolute efficiency value approaches a steady value and the relative variance decreases as the number of source particle increases. The calculated spectrum is normalized to the experimental ones absolutely by multiplying the number of photons emitted by $^{137}$Cs source during a time interval for which the experimental PHS is recorded. To do this, the values of the simulated PHS are multiplied by a factor (source activity x acquisition time of experimental spectrum) which allowed direct comparison with the experimental spectrum corrected for background or the experimental data are divided by the same factors to compare with the MCNP simulated PHS

5. Results and Discussion

The result of MCNP PHS simulations for glycerin enclosed in glass pipe and their comparison of the spectral shape with the experimental ones are shown in Fig. 2. A good agreement in the shape of the PHS is seen between the experimental spectra and those of MC simulated ones. Thus measurements support the MC simulations. The voxel position and its size are calculated from the size of the collimators and source-sample and sample-detector distances. The mass attenuation coefficients for the incident and scattered energies $\mu/\rho$ and $\mu'/\rho$ respectively are computed using the XCOM program [24]. The densities of the various fluids with reference to that of water are obtained from the experimental scattered counts corrected for attenuation employing the equation 3 and are given in Table 1. The errors resulting from estimation of geometrical parameters and cross sections are eliminated in the density calculation (equation 3) by taking the ratio of measured scattered intensities in the same geometrical setup with respect to water sample. The total uncertainty in the derived density is around 3% and can be further
reduced by minimizing the statistical uncertainties associated with measured scattered intensity. The measured densities from scattering method are closer to standard densities and the percentage deviations of measured density from standard density are given in Table 1. The densities from the transmission experiments are determined following the standard procedure. It can be seen from the Table 1 that the percentage deviations are higher in the case of transmission method compared to scattering method. The density resolution one can obtain from the scattered/transmitted methods is determined from the least squares method. The least square fits of scattered and transmitted intensity data for different liquids are given in Table 2.

### Table 1. The measured densities (kg/m³) of hexane, olive oil, castor oil and glycerin by gamma scattering and transmission methods along with standard values

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Standard density</th>
<th>Measured density</th>
<th>% deviation from standard density</th>
<th>Measured density</th>
<th>% deviation from standard density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexane</td>
<td>654.8</td>
<td>651.4±25.9</td>
<td>0.52</td>
<td>790.1±9</td>
<td>21.54</td>
</tr>
<tr>
<td>Olive oil</td>
<td>800-900</td>
<td>889.1±35.29</td>
<td>4.60</td>
<td>891±11</td>
<td>4.71</td>
</tr>
<tr>
<td>Castor oil</td>
<td>961</td>
<td>956.3±37.9</td>
<td>0.49</td>
<td>1020±12</td>
<td>6.25</td>
</tr>
<tr>
<td>Glycerin</td>
<td>1261</td>
<td>1189.8±46</td>
<td>5.65</td>
<td>1141±14</td>
<td>9.52</td>
</tr>
</tbody>
</table>

### Table 2. The least square fit data of scattered and transmitted photons intensity for fluids

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Scattering method</th>
<th>Transmission method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured intensity</td>
<td>Calculated intensity</td>
</tr>
<tr>
<td></td>
<td>Measured intensity</td>
<td>Calculated intensity</td>
</tr>
<tr>
<td>glycerin</td>
<td>3536</td>
<td>3486.7</td>
</tr>
<tr>
<td>water</td>
<td>3244</td>
<td>3213.7</td>
</tr>
<tr>
<td>olive oil</td>
<td>3075</td>
<td>3167.7</td>
</tr>
<tr>
<td>hexane</td>
<td>2803</td>
<td>2766.5</td>
</tr>
</tbody>
</table>

The slopes obtained from these fits directly give the density resolution one can obtain from scattered and transmitted experiments. The density resolution in the case of scattering method is higher by a factor of 3.43 compared to transmission method and indicates the superiority of the scattering method. A good contrast/sensitivity assures a large change in measured parameter (counts) on a small variation in physical parameter (density). Sensitivity and contrast mainly depends on the difference in measurement counts. This has obvious consequences for studying density measurements for solutions (miscible and immiscible) and slurries in pipelines on-line using this method. The bulk density of slurries can be used for the calculation of solid weight fraction. The fluids interface levels of immiscible fluid combinations of olive oil- glycerin, castor oil- glycerin, hexane- water are measured by gamma scattering and transmission methods. The measured counts as a function of fluid height for glycerin-olive oil combination are shown in fig 3 along with the least square fitted interface levels. The immiscible fluid interface levels derived
through least square fitting of measured scattered and transmitted intensities measured around the interface regions are given in Table 3. The measured immiscible fluid interface levels from

![Graph showing scattered and transmitted intensities](image)

Figure 3. The measured counts as a function of fluid height for glycerin-olive oil combination

**Table 3. The measured immiscible fluid interface levels in meter (measured from the bottom of the glass container) along with levels derived from scattering and transmission methods**

<table>
<thead>
<tr>
<th>Immiscible fluid combination</th>
<th>Actual level</th>
<th>Measured level</th>
<th>% deviation from actual level</th>
<th>Measured level</th>
<th>% deviation from actual level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-hexane</td>
<td>0.105</td>
<td>0.0991±1.82e-3</td>
<td>6.164</td>
<td>0.0968±7.5e-4</td>
<td>7.733</td>
</tr>
<tr>
<td>Glycerin-castor oil</td>
<td>0.105</td>
<td>0.1061±1.87e-3</td>
<td>1.176</td>
<td>0.0981±7.05e-4</td>
<td>6.552</td>
</tr>
<tr>
<td>Glycerin-olive oil</td>
<td>0.105</td>
<td>0.1071±1.85e-3</td>
<td>2.195</td>
<td>0.0979±7.4e-4</td>
<td>6.752</td>
</tr>
</tbody>
</table>

![Image of water-hexane combination](image)

Figure 4. The Image of the water-hexane combination without (left) and with (right) attenuation correction

![Image of water-hexane combination with attenuation correction](image)

Figure 5. The attenuation corrected images of immiscible fluid combinations in various containers

scattering method are closer to actual levels and it can be seen from the Table 3 that the percentage deviations are higher in the case of transmission method compared to scattering method. Fig.4. shows the images of water–hexane combination obtained from raw scattered
counts and the attenuation corrected counts and fig. 5 shows the images obtained from attenuation corrected counts of glycerin– castor oil, glycerin– olive oil and water-n hexane combination in PVC, SS and glass pipe. These images were reconstructed from sequential vertical and lateral scanning of liquid columns in steps of 0.002m using the MATLAB. The attenuation correction enhances the contrast of the images and the water– hexane interface becomes clearly visible and is shown in fig.4 and the blue region represents air column.

5. Conclusions
A gamma scattering scanning system for fluid interface level determination and density measurement, that require access only to the one side of a sample to be inspected is described. The measured densities from scattering method are closer to standard densities and the percentage deviations are higher in the case of transmission method compared to scattering method. The density resolution in the case of scattering method is higher by a factor of 3.43 compared to transmission method and this indicates the superiority of the scattering method. This has obvious consequences for studying density measurements for solutions (miscible and immiscible) and slurries in pipelines on-line using this method. The measured immiscible fluid interface levels from scattering method are closer to actual levels and the percentage deviations of measured levels are higher in the case of transmission method compared to scattering method. The measurements support the MC simulations. The main advantages of the scattering method as compared to other techniques are the ability to detect fluid interface level in immiscible combinations without the need for all-round access and contact with the sample under investigation and it is also possible to inspect a chosen volume or point.

References