INTRODUCTION

The need for advanced Non Destructive Evaluation (NDE) techniques to inspect relatively thick material or structure with access only to the one side of the sample has drawn attention to x-ray or gamma backscatter as a desirable choice. 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. 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. 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. Collimated gamma rays are used in both transmission and back scattering geometry for the fluid level gauging [1]. Density measurements for solutions (miscible and immiscible) and slurries in pipelines are carried out on-line using this method [2].

The present work focuses on the interface level detection and density determination of fluids, immiscible fluid-fluid combinations and fluid-air combination enclosed in cylindrical glass tubes by gamma scattering and the results are compared with gammatography technique. The PC controlled gamma scattering scanning system developed indigenously has been successfully employed 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. The scattered intensity depends on the effective density and thickness of the sample within the voxel and the densities are determined by iteration method from the scattered intensities, mass attenuation coefficients and the geometrical parameters. The iterated densities and measured interface levels are compared with those values obtained from transmission technique. The density resolution from the scattered/ transmitted methods is determined from the least squares method. The MC numerical simulation of the scattering phenomena is done using the MCNP code and the spectra are compared with experimental ones.

THEORY

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 and given by the equation:

$$I(P) = I_0 \exp \left[ -\frac{\sigma(E_e)}{\rho} \int dx \frac{\delta(E,\theta)}{\delta \Omega} \right]$$

(1)
where \( I_0 \) is the incident intensity, \( \mu(E)/\rho \) is the mass attenuation coefficient of the fluid for the incident energy, \( \mu(E)/\rho \) is the mass attenuation coefficient of the fluid for the scattered energy, \( \text{d} \sigma(E, \theta)/\text{d} \Omega \) is the differential scattering cross section given by Klein-Nishina relation, \( \text{d} \Omega \) is the solid angle subtended by the detector and its collimator, \( V \) is the voxel volume, \( \rho(P) \) is the material density at any scattering point \( P \), \( N \) is the Avogadro’s number, \( Z \) is the atomic number and \( A \) is the atomic weight. For a fixed source and detector positions and the collimator sizes, equation (1) reduces to:

\[
I(P) = K \rho \exp \left[ \left( \frac{\mu(E)}{\rho} \right) \rho \xi \right] \exp \left[ \left( \frac{\mu(E)}{\rho} \right) \rho \xi \right] \tag{2}
\]

where,

\[
K = I_0 \frac{d\sigma}{d\Omega} (E_0, \Omega) S(E_0, \Theta, \Omega) \rho x^n \rho y^n \rho z^n \tag{3}
\]

K is a constant for a given experimental setup. Equation (2) clearly establishes the relation of density of the scatterer with the scattered count.

### Attenuation and Multiple Scattering Correction

The number of detected photons depends on the number of scattered photons, as well as on the attenuation along all the path within the material. The attenuation factor is calculated theoretically by employing the method described in the reference [3-4]. 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 coefficient 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 \( \exp(\mu dl) \) over the path length. The total scattered attenuation correction is also calculated in the same method by assigning the attenuation coefficient corresponding to scattered energy as pixel value and by simulating the scattered path. The attenuation corrected scattered count is given by:

\[
I_{\text{corr}} = I(P) \exp \left[ \sum \mu dl \right] \exp \left[ \sum \mu dl \right] = K \rho \tag{4}
\]

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.

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. The detector collimator employed in the present experiment can be expected to exclude most secondary scatter by reducing the voxel and the usage of high energy resolution detector HPGe and setting a smaller energy window width \( \Delta E \) around the Compton peak separates most of the multiple scattering contribution. The multiple scattering component within the voxel and energy window width \( \Delta E \) is calculated by MC method.

### EXPERIMENTAL PROCEDURE

The experimental set-up is an automated PC controlled 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 \(^{137}\text{Cs} \) 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 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 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 and PVC cylindrical container 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 x 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 \(^{137}\text{Cs} \)) 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

### 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 \(^{137}\text{Cs} \) radioactive source , HPGe detector and the sample are modeled according to the
experimental set-up. 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 re-binned to the same energy grid as the MCNP calculation for the purpose of comparison. Each simulation is run with 2.1 billion source particles. 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

**RESULTS AND DISCUSSION**

The result of MCNP PHS spectral shape simulations are compared with the experimental ones. A good agreement in the shape of the PHS is seen between the experimental spectra and those of MC simulated ones. The voxel position and its size are calculated from the size of the collimators and source-sample and sample-detector distances. 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. The multiple scattering contributions are estimated by following an extrapolation method [5]. The total scattered intensities from different sample thicknesses within the present voxel and energy window width $\Delta E$ are calculated by MC method. These calculated intensities are extrapolated to zero sample thickness to obtain the single scattered intensity free from multiple scattering. The interpolated values are compared with experimental intensities corrected for self absorption to estimate the multiple scattering contributions and found to be in the same range within 10 to 12% for all the fluids studied. The multiple scattering contribution and the errors resulting from estimation of geometrical parameters and cross sections are minimized in the density calculation (equation 3) by taking the ratio of measured scattered intensities in the same experimental setup with respect to water sample. The measured densities from scattering method are closer to standard densities compared to those obtained by transmission method. The density resolution one can obtain from 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. For the present incident and scattered energy regions, Compton scattering cross section is relatively high for low- Z fluid materials employed in the present investigation compared to photoelectric cross section. Moreover Compton scattered signal depends strongly and linearly on density of the scattering medium. For thin samples ($\mu << 1$) and low-Z fluid materials absorption is relatively less and hence change in transmitted intensity will be very feeble. Due to all these factors scattering technique yields better sensitivity and contrast compared to transmission method. 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 glycerin- olive oil, glycerin- castor oil, water- hexane are measured by gamma scattering and transmission methods. The measured counts as a function of vertical level for glycerin-olive oil fluid-fluid interface along with the least square fitted interface levels are shown in fig.1 The intensity of the scattered

**Table 1 :** 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>Scattering</th>
<th>Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual level</td>
<td>Measured level</td>
</tr>
<tr>
<td>Water-hexane</td>
<td>0.105</td>
<td>0.0991±1.82e-3</td>
</tr>
<tr>
<td>Glycerin-castor oil</td>
<td>0.105</td>
<td>0.1061±1.87e-3</td>
</tr>
<tr>
<td>Glycerin-olive oil</td>
<td>0.105</td>
<td>0.1071±1.85e-3</td>
</tr>
</tbody>
</table>

![Fig. 1 : The measured counts as a function of fluid height for glycerin-olive oil combination](image-url)
Fig. 2: The image of the water-hexane combination without (left) and with (right) attenuation correction.

Fig. 3: The attenuation corrected images of immiscible fluid combinations in various containers.
counts is same within the statistical uncertainties as long as the voxel is in high density fluid region of the immiscible fluid combination. As voxel moves towards the interface, the scattered counts decrease gradually due to the increased amount of contribution from low density fluid. The steep decrease in the scattered counts corresponding to vertical scanning point in the down slope region is the first point of least square fitted region and the starting of constant region in the scattered counts is the last point. The selected regions for least square fitting of the scattered and transmission methods are different due to different voxel sizes in these methods. The midpoint of the fitted region is taken as the interface level and the measured interface levels from scattering method are closer to actual levels. The interface level representing the midpoint of the fitted region is not affected by the multiple scattering. This is due to presence of almost same amount of multiple scattering in all of the points used for fitting. The measured immiscible fluid interface levels derived through least square fitting from scattering method are closer to actual levels and 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 results for different immiscible fluid combinations are obtained with the same glass container after correcting for self absorption. Fig.2 show the images of water–hexane combination obtained from raw scattered counts and the attenuation corrected and fig. 3 show the images obtained from attenuation corrected counts of glycerin–castor oil, glycerin–olive oil and water–hexane combination in PVC, SS and glass pipes. The attenuation through the different container material is also taken into consideration in reconstructing these images. 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.2 and the blue region represents air column. This shows that these measurements can be done in any container materials without sacrificing the contrast by applying suitable attenuation corrections.

REFERENCES
4. P Priyada, M Margret, R Ramar and Shivaramu, Applied radiation and Isotopes ( In press)