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Investigation of Incoherent Gamma-ray Scattering Potential for the Fluid Density Measurement

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Abstract. Incoherent gamma ray scattering is a method that can be applied for the fluid parameter characterization. The aim of the present work is to study the potential usage of the incoherent gamma ray scattering measurements to evaluate the fluid density based on the Monte Carlo approach. Enlarging the density of a fluid results in a significant reduction in the intensity of the detected gamma scattering. The difference of the simulation curve slope results in the gamma transmission mode its about 0.02 compared to the experimental result.

Introduction

Gamma-ray spectrum measurement is one of the promising methods in the non-destructive test (NDT) application, especially for an online measurement. It is applicable for many industrial applications such as in medical tomography, mining, oil industry, and homeland security. One type of gamma-ray spectrum measurement is an incoherent scattering measurements.

Incoherent scattering is a type of interaction that occurs when the radiation penetrates through certain materials. The direction of scattered radiation and its energy change due to the photon interacting with an electron of the material. According to the relation between the density of the material and the electron density, the radiation scattering method is applicable to be used in the investigation of the material density. In 1998, Ball et al. have investigated the response of gamma backscattering to the spatial density in bulk sample [1]. Jahanbakhsh et al. investigate the possibility of using weak gamma sources in the Compton scattering for density investigation of bulk samples [2]. For the fluid analysis, Khorsandi and Feghhi have used the transmission mode in density analysis [3]. Hussein (2011) has developed investigation of the fluid flow in the pipe [4].

In the recent years, numerical simulations become more important in the development of NDT field. Especially in order to describe a sensor or probe model design, performance of inspection modelling, and interpretation of experimental data [5]. The Monte Carlo method is one type of numerical simulations that has capabilities in the implementation of the several of physics models and give the predicting results in the radiation physics application [6]. In the present study, we investigated the potential of the incoherent gamma-ray scattering measurements in the fluid density measurement using the Monte Carlo approach from a GEANT4 simulation toolkit.

Methodology

In the gamma ray energy spectrum measurement, there are two kinds of gamma ray spectrum measurements i.e. transmission and scattering. In the scattering, the scattered photon from an interaction have an altered direction and energy. Scattering interactions that may occur are the single scattering or multiple scattering. The photon beam intensity has attenuated according to the Beer–Lambert law in the path to the scattering point interaction and in the path to the detector after the scattering [7]. Fig. 1 shows the single scattering interaction of photons with an element volume

dV in the medium. The intensity of the detected photon is influenced by some parameters as depicted in the following formula.

$$dI = \left(\frac{S r_0^{\,2} N_A Z A_d}{8\pi M} \right) \rho \times \frac{e^{-\left(\frac{\mu_1(E)}{\rho}\right)\rho r_1}}{r_1^2} \times \frac{e^{-\left(\frac{\mu_2(E)}{\rho}\right)\rho r_2}}{r_2^2} \times \left(P - P^2 \sin\theta + P^3\right) \sin\beta \cos\phi \, dV \qquad (1)$$

where S is the source activity (photon s^{-1}), r_0 is the classical electron radius (2,82 fm), N_A is an Avogadro number, Z is the atomic number, A_d is the detector surface area, M is the atomic mass, ρ is the material density, dV is element volume interaction, r_1 and r_2 are the long path of the primary photon before interaction and after scattering, respectively. The parameter P is the scattering parameter which a function of incident photon energy and scattering angle θ,

$$P(E,\theta) = \frac{1}{1 + E(1 - \cos\theta)} \qquad (2)$$

where constant $E \equiv h\nu \,/\, m_0 c^2$ [1,7].

The solution of the equation (1) was determined in the simple form as

$$I(\rho) = A\rho e^{-\rho B} \qquad (3)$$

where A and B are constant.

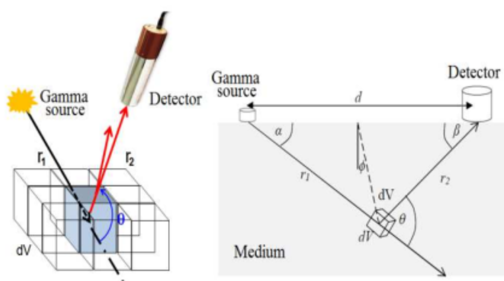

Fig. 1 Schematic diagram of photon scattering interaction with an element volume dV (adopted from Devlin and Taylor) [8]

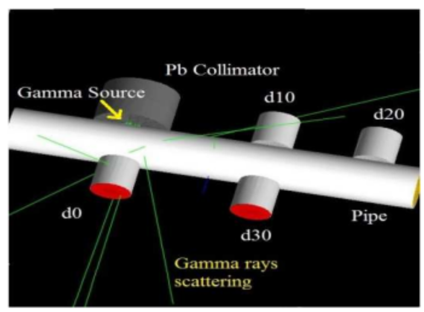

Fig. 2 Schematic GEANT4 visualization of the measurement setup model

In this work, the simulation was conducted based on GEANT4 Penelope Monte Carlo using 5.0 x 10^7 of the gamma source beamon. Four detectors (d0, d10, d20 and d30) are placed in two type positions as shown in Fig. 2. Detector d0 represents the transmission measurements performed experimentally by Khorsandi and Feghhi [3]. Three others detector is placed in order to the photon scattering measurements. The spatial distance between detector d10 and the collimated source axis are about axis 27.5cm. Detector d20 is placed 20cm far away from detector d10. The polyethylene pipe has an inner radius 5 cm and the thickness is about 2.0 mm. Fluids under investigation inside the pipe (i.e. gasoline, gasoil and water) assumed to be of uniform density ρ ($\rho_{gasoline}$ = 0.752 gr/cm^3, ρ_{gasoil} = 0.850 gr/cm^3 , ρ_{water} = 0.998 gr/cm^3). A disk gamma ray source model is used for Cs-137 source and it' s collimated by the cylindrical shielding lead of 5cm thickness. The 3in. x 3in. NaI(Tl) detector model reconstruction in the simulation is adopted from references [9, 10]. ROOT package is used for the Gaussian peak curve analysis.

Results and Discussion

Response Function. Fig. 3 shows the detector response function of GEANT4 simulation result (1 x 10^8 beamon and 2.67 scaling factor) compared to the spectrum measurement. The Cs-137 gamma source is placed in front of the collimated NaI(Tl) 3 in. x 3 in. scintillation detector (2 cm hole diameter of collimated Pb). There is a good agreement for photopeak energy between the simulation result and the experimental result.

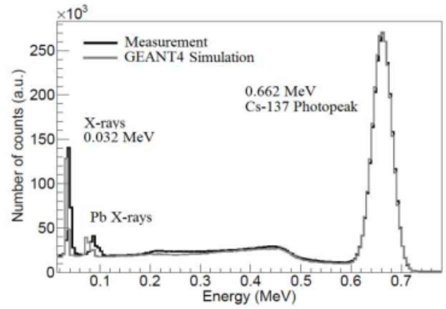

Fig. 3 Response function of Cs-137 15μCi gamma source for 3 in. x 3 in NaI(Tl) detector

Based on the detector construction setup, then we analyze the detector response function of simulation results. Fig. 4 shows the response function result of the detector that placed in the four different positions for three different types of density fluid i.e. gasoline, gasoil and water. Fig. 4 (A) shows the transmission energy spectrum measurement. In addition, for the scattering energy spectrum measurement result of detector d10, d20 and d30 described in Fig. 4 (B-D).

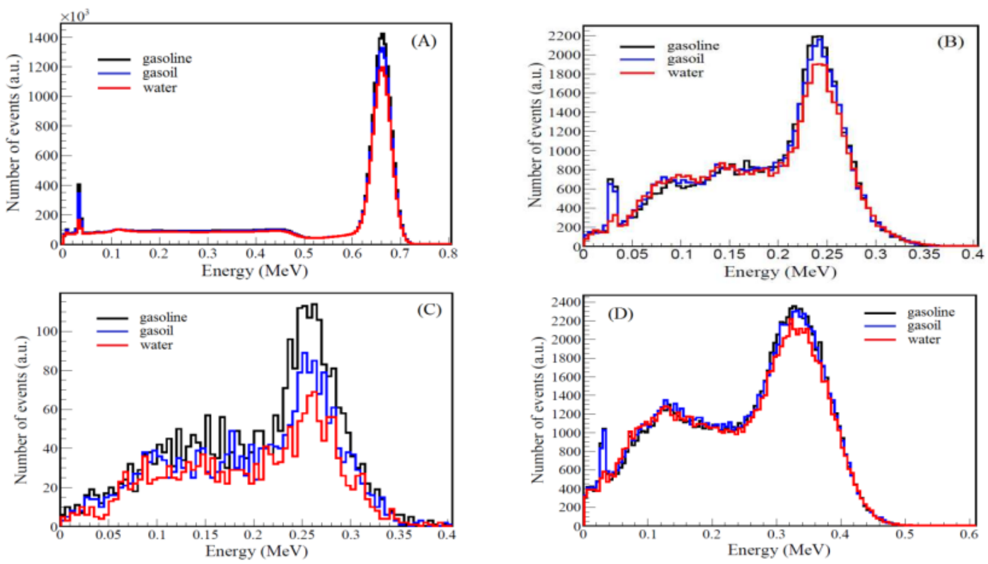

Fig. 4 Response function of detector NaI(Tl) 3in. x 3in. from GEANT4 simulation: (a) d0 detector position; (b) d10 detector position; (c) d20 detector position; (d) d30 detector position

The density of fluid matter gives an effect to the gamma energy spectrum as shown in that figure. The gasoline has a lower density number, but it shows a higher intensity (number of events) of gamma ray energy detected compared to the gasoil and water. The increased density of fluid will increase the number of electrons at the scattering point interaction, attenuation of primary and scattered photons. Therefore, it results in an effect to the decreasing of the detected intensity or the peak of energy spectrum.

Peak Spectra Analysis. In the transmission mode measurement which conduct by the d0 detector showing the main peak of Cs-137 gamma source is observed in the 0.662 MeV energy channels (Fig.4 (A)). According to the linear curve fitting result as shown in Fig. 5, the normalized area under the peak curve intensity shows that the GEANT4 simulation result has a good agreement with the Khorsandi experiment result. These results show that the GEANT4 model can be used for predicting experiment results of fluid density measurement especially for the gamma scattering measurement.

Here in the Fig. 6, we have the same trends of the scattering energy spectrum. The decreasing of the photopeak height due to the fluids density increase can be observed. According to the equation (3), the proposed constant A and B for the curve fit in the Fig. 6 are presented in Table 1.

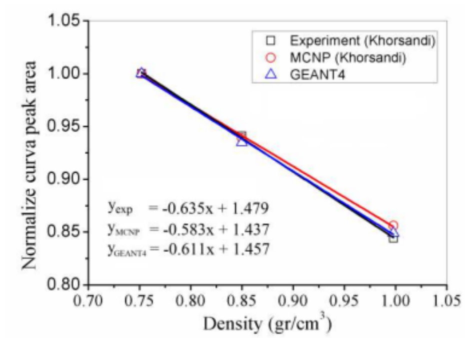

Fig. 5 Normalize of the area under the peak curve of transmission mode (d0 position)

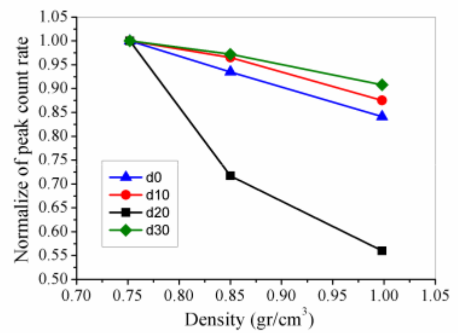

Fig. 6 Gaussian height curves of photopeak at four different detector positions (scattering and transmission mode)

Table 1. Curve fitting constant

Fitted function $y = A\rho e^{-B\rho}$			
Detector position	Constant A	Constant B	Correlation coefficient
d0	7435670.237	1.854	0.998
d10	9725.511	1.693	0.998
d20	1932.609	3.637	0.977
d30	10035.401	1.545	1.000

Based on the B constant of the four normalized peak count rate curves, d20 detector position have a higher decreasing slope than the others. In other side, the number of entry photon to the detector d20 position is too small, so that this configuration setup needs the higher activity source.

Conclusions

In this study, a Monte Carlo simulation of scattering and transmission measurements of Cs-137 0.662 MeV gamma source for the fluid density measurement was carried out using GEANT4. Increasing the density of a fluid caused a significant decrease in the intensity of the detected gamma scattering. The deviation of the simulation curve slope results in the gamma transmission mode it's about 0.02 from the experiment curve result. In order to make a scattering measurement of fluid density, d20 detector position is appropriate with a higher activity source.

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