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A portable tomography system with seventy detectors and five gamma-ray sources in fan beam geometry simulated by Monte Carlo method

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ABSTRACT

This paper describes the Monte Carlo simulation, using MCNP4C, of a portable instant non-scanning tomography containing five radioactive sources with the same activities and seventy NaI(Tl) detectors constituted of five sets of fourteen detectors, diametrically opposite to each radioactive source. The detector was validated by comparison with the experimental measurements. The full width at half maximum (FWHM) deviation between the experimental and the simulated spectra was 3.5%. A steel pipe of 17 cm×0.5 cm (diameter×thickness) containing water and two dynamic bubbles of 2 cm and 4 cm diameter were simulated. The SIRT algorithm was used to reconstruct the images. The simulated images are presented in frames. On the first frame, no bubble is observed. On the subsequent frames, the growing of the bubbles is observed, reaching the maximum diameter; after that, the bubble begins to decrease progressively, until its disappearance. The measured bubble diameters generated by simulation were 43 ± 3 mm and 27 ± 2 mm for the bubbles of 40 mm and 20 mm diameters, respectively. The spatial resolution of the proposed simulated tomography was estimated by the Modulation Transfer Function (MTF), presenting a spatial resolution of 18.3 mm and 20.2 mm for samplings at ^{137}Cs photopeak and full window, respectively.

1. Introduction

The industrial distillation system involves fast dynamic processes containing solid, liquid and gas mixtures. The distillation columns are, usually, built with steel and have large diameters and thicknesses that make their analysis unfeasible with conventional X-ray beams [1,2]. For this reason, gamma radioactive sources in the energy ranges of 317 keV (^{192}Ir), 662 keV (^{137}Cs) to ~1250 keV (^{60}Co) are preferable, instead of low X-ray energy sources [3]. While for medical tomography, the patient goes to the computed tomography system (CT), for industrial applications, the CT system should be transported up to the object (pipe or column) and, mechanically, adapted to the object setting. In addition, industrial tomography system should be adapted for different sizes of objects that are usually located in a hostile environment, containing flammable superheated materials, occasionally subjected to high internal pressure and presenting many difficulties for placing CT devices around these objects. Besides, the phenomena related to multiphase processes are usually fast, requiring high time resolution of the CT data acquisition [1,2,4]. In such case, ideally, the tomography system should be fixed and it is not necessary to move its sources and detectors around the object. Portable instant non-scanning (fourth generation like) and fifth generation tomography systems [5,6] meet these requirements. Additionally, the system should be light enough to be portable and easily installed.

Nowadays, most tomography systems do not meet these requirements and are used in laboratory environment to study and to optimize column designs and industrial processes; however, in practice, these devices are not suitable to be used in industrial plants for real time measurements.

At the University of Bergen, Norway, a high speed tomography system was developed [5,7,8], fact that served as inspiration for the portable instant non-scanning tomography designed and developed in IPEN Laboratory. The Bergen tomography system uses semiconductor detectors of CdZnTe (CZT) and five ^{241}Am sources. The CZT detectors are fixed on the printed circuit board and collimated on a complex system what makes it difficult their use for larger objects. The system was designed for a maximum pipe diameter of 80 mm [5,7,8]. Also, the use of CZT semiconductor detectors of low thickness (~1 mm) and radiation source of low energy, like the 60 keV ^{241}Am radiation, makes this tomography system not suitable to be used in the measurements of high density objects [9]. In order to be applicable, practically, in industrial plants, portable instant non-scanning tomography system, inspired in the Bergen tomography system, is being developed. However, in the industrial process plants, the analyzed objects have,

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typically, high density materials and large dimensions in their structure, such as the columns/pipes used in oil refineries, chemical, textile and petrochemical areas. Consequently, a high energy radiation source is required in order to cross the material, usually, 667 keV ^{137}Cs and ~1252 keV ^{60}Co. Therefore, dense detector material may be necessary to absorb the photons from the source [3,4]. Scintillation detectors, such as, NaI(Tl) (3.76 g/cm^3) BGO ($Bi_4Ge_3O_{12}$, 7.13 g/cm^3), LYSO ($Lu_{0.6}Y_{1.4}SiO_{0.5}$:Ce, 5.37 g/cm^3), LSO (7.35 g/cm^3) and GSO (6.71 g/cm^3) are widely used in tomography applications [3,4,10]. In our laboratory, a portable instant non-scanning tomography, that is, intrinsically, a fourth generation like tomography is being developed, comprising several sets of 2.5×5.0 cm (diameter and length) NaI(Tl) detectors and five shielding cases for radioactive sources. Each shielding case is placed diametrically opposite to a fan detector set, as showed in Fig. 1. All scintillating detectors cited meet the requirements for this project. The main criterion of choice of the NaI(Tl) was its relatively low cost compared to the other detectors suitable for the proposed application. Furthermore, it is capable to detect a large range of energies, i.e. from 60 keV ^{241}Am to ~1252 keV ^{60}Co and it has higher light output. The choice of the source to be used depends on the material densities, wall thickness and dimension of the object to be evaluated by tomography measurements. Also, the proposed tomography system may be adjusted to different dimensions of objects (columns or pipes) by changing the number of detector sets and the distance among detector, sources and object. Thus, the tomography system has the capacity of being adapted and applied for objects of different shapes and dimensions, such as, column or pipe sizes found, usually, in the industrial plants. The tomography system may be mounted on a wooden platform, which is lightweight to be replaced in future applications, according to the challenges of new geometry, dimension of the objects and application requirements..

2. Monte Carlo simulation

Monte Carlo method is a simulation tool widely used for radiation transport. This calculation technique may be applied to a wide variety of applications in the radiation field, such as radiological protection, nuclear installations, shielding and detectors modeling among several other purposes [11,12]. Its use is recommended in the first stage of the project development, in order to know its feasibility and to guide the selection of the best methodology available. Monte Carlo method is applied in this study to estimate the expected results of a portable industrial tomography, under development in our laboratory, which contains 70 NaI(Tl) detectors that surround the object in fan-beam type configuration and five source-cases that are distributed, diametrically, in front of each set of 14 detectors, as showed in Fig. 1.

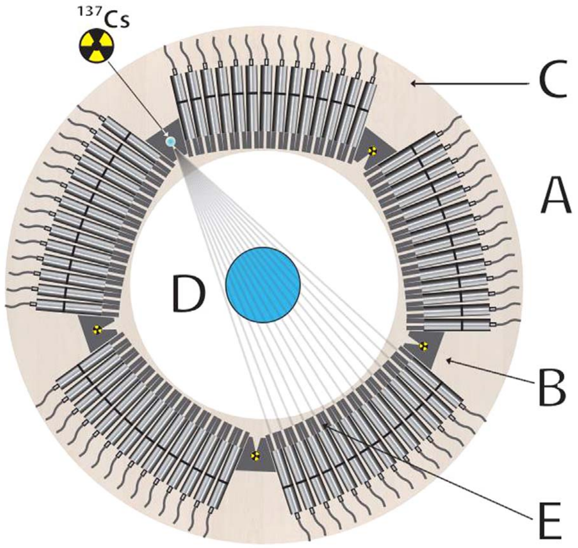

Fig. 1. Portable instant non-scanning tomography design for multiphase analysis. NaI(Tl) detectors (A), radioactive shielding case (B), wooden platform (C), the multiphase object to be analyzed (D) and detector collimator (E).

The MCNP4C (Monte Carlo N-Particle) version 4C code [13] is a general purpose Monte Carlo radiation transport designed to track different types of particles (neutrons, electrons, gamma rays), over a broad range of energies. The code obtains the solution of the problem by simulating individual particle trajectories and recording some aspects of their average behavior [14]. The process consists of following each of the many particles since their emission from a source up to reaching the energy threshold. The radiation energy is transferred to the matter by absorption, escape, physical cut-off and other processes. Probability of distributions is randomly sampled using transport data to determine the outcome, at each step of the trajectory. The quantities of interest are tallied along with estimates of the statistical precision of the results. The MCNP4C code may be used to simulate gamma-rays interactions, which comprise: (i) incoherent and coherent scattering; (ii) the possibility of fluorescent emission after photoelectric absorption; (iii) pair production with local emission of annihilation radiation and Bremsstrahlung effect [15].

When performing the mathematical simulation of NaI(Tl) detectors, in order to obtain their response curves, some corrections should be made to improve the simulation and approach the real case. Two of the main corrections are essential: the determination of the photon detection efficiency and the energy resolution, which is related to distinguish different peaks very close to each other, in the energy spectrum. Their determination has great importance when performing the identification of radionuclides or when simulating detectors that approximate the real case [14,16].

In practice, the energy resolution (R_E), as shown in Eq. (1) of the detector, is given by the full width at half maximum (FWHM) of the Gaussian peak (pulses per channel) for a given energy (E_0).

$$R_E=\frac{FWHM}{E_0} \tag{1}$$

where, R_E is the energy resolution, FWHM is the full width at half maximum of the photopeak, E_0 is the central energy of the photopeak [14,17].

Some of the effects related to the photopeak are inherent to the electronic circuit of the spectrometric system, which is not simulated by the MCNP4C. Thus, to obtain a more realistic detector response and to consider this effect in the simulation, it is necessary to achieve, experimentally, adjustment parameters of the detector energy resolution and apply a MCNP4C code function to fit Gaussian to the spectrum obtaining the suitable corrections [14].

The MCNP4C fitting technique to consider the resolution of the real detector, measured experimentally, consists of using a "ft8 geb" card into the input file of the code. The tallied energy is broadened by sampling from Gaussian, what is done by the Eq. (2).

$$f(E)=Ce^{-\left(\frac{2\sqrt{\ln 2}\,(E-E_0)}{FWHM}\right)} \tag{2}$$

where, $\boldsymbol{E}$ is the photopeak energy, $\boldsymbol{E_O}$ the energy of the tally, not broadened, and $\boldsymbol{C}$ is the normalization constant.

The energy resolution of the simulated detector may be evaluated by the Gaussian Energy Broadening (GEB) command, which is used as input to the MCNP4C code function [15]. This command is a special treatment for tallies to better simulate a physical radiation detector. For this purpose, an adjustment by non-linear least-squares procedure is applied to calculate the values of "***a***", "***b***" and "***c***" coefficients from Eq. (3) [14]. These parameters are used with GEB command.

$$FWHM=a+b\sqrt{E+cE^2} \tag{3}$$

where, $\boldsymbol{E}$ is the energy of the incident gamma ray energy (MeV). This Eq. (3) may be simplified on Eq. (4).