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Optimization of detection geometry for industrial SPECT by Monte Carlo simulations

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ABSTRACT: The Korea Atomic Energy Research Institute (KAERI) has developed an industrial SPECT to investigate the fluid flow and mixing patterns in columns. It has been found that the industrial SPECT is indeed a very powerful tool to study the hydrodynamics in multiphase reactors. One of the practical issues in the development of industrial SPECTs is to achieve a required imaging resolution of an industrial SPECT with a minimum number of component detectors, the number of which is frequently limited by both the size of the detectors and the total cost of the imaging system. In the present study, a set of different geometries of industrial SPECTs were evaluated by Monte Carlo simulation using MCNPX to determine the minimum number of detectors that will provide a spatial resolution that corresponds to 10% of the cylindrical column diameter. Our results show that 11 and 12 detectors will satisfy the 10% resolution requirement for the 40 cm and 60 cm diameter columns, respectively, for the industrial SPECT and radioisotopes considered in the present study. The conclusion of this result is valid only for the case considered in the present study, but we believe that the same procedure can be applied to other industrial SPECTs for this kind of optimization.

KEYWORDS: Radiation monitoring; Inspection with gamma rays

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Contents

1 Introduction 1

2 Materials and method 1

3 Results 3

4 Conclusions 5

1 Introduction

Industrial multiphase reactors the main purpose of which is transportation, mixing, and reaction of fluids, have been used widely in the chemical, materials, fuel and food processing industries. The prediction of performance of multiphase reactors is affected by our ability to quantify the hydrodynamics in the reactor. The study of hydrodynamics in industrial multiphase reactors increasingly depends on non-invasive techniques using gamma radioisotopes [1]. Legoupil et al. proposed a portable single photon emission computed tomography (SPECT) system to measure the flow fields in multiphase reactors [2]. The portable SPECT system provided the information of flow and mixing patterns in a bi-dimensional vessel, but the performance of the portable SPECT was not enough to acquire satisfactory image resolution.

Recently, the Korea Atomic Energy Research Institute (KAERI) has developed an industrial SPECT based on the portable SPECT system to study the flow fields in multiphase reactors, and a significant amount of effort has been made to improve the performance of the industrial SPECT [3, 4]. It has been realized that one of the practical issues in the development of industrial SPECTs is to achieve a required imaging resolution with a minimum number of component detectors, the number of which is frequently limited by both the size of the detectors and the total cost of the imaging system. In the present study, a set of different geometries of industrial SPECTs was evaluated by Monte Carlo simulation using MCNPX to determine the minimum number of detectors that will provide a full width at half maximum (FWHM) of the profile corresponding to 10% of the cylindrical column diameter, which is considered sufficient for most industrial applications.

2 Materials and method

In the present study, industrial SPECTs were simulated using the MCNPX code [5]. For the simulation, the industrial SPECTs were assumed to be composed of six detector arrays arranged in a stationary hexagonal shape to surround the imaging object, i.e., a cylindrical column. The collimator width and collimator hole width were fixed as 2.9 cm and 1.2 cm, respectively (figure 1). The depth of the collimator hole was determined by equation (2.1)

$$\frac{\mathrm{FWHM_c} \times \text{Number of detectors}}{\text{Column diameter}} = 1.5\,, \tag{2.1}$$

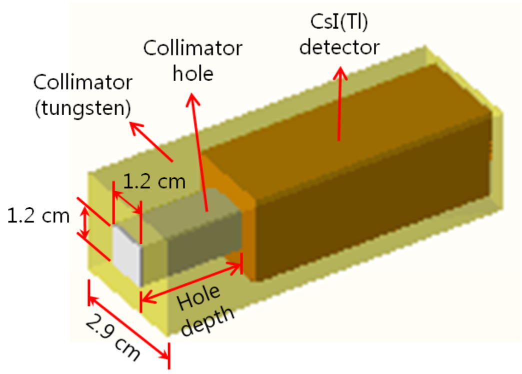

Figure 1. Geometry of collimator.

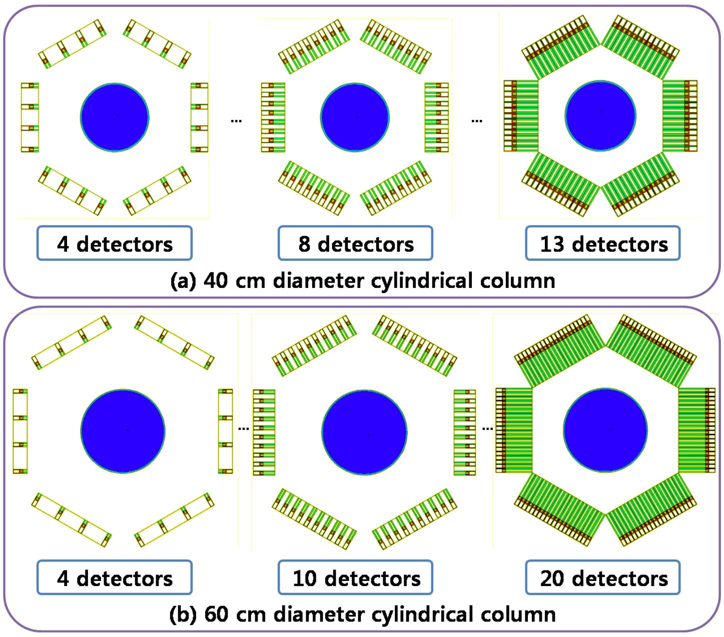

Figure 2. Schematic diagrams of (a) 4, 8, and 13 detectors for the 40 cm diameter column and (b) 4, 10, and 20 detectors for the 60 cm diameter column.

where

$$\mathrm{FWHM_c} = \frac{\text{Collimator hole width} \times \text{Distance between detector and column center}}{\text{Collimator hole depth}}\,.$$

The distance between detector and column center was set to be 48 cm for 40 cm diameter column and 71 cm for 60 cm diameter column.

The size of the CsI(Tl) scintillation crystals, placed in a tungsten collimator, were assumed to be 1.2 cm $\times$ 1.2 cm $\times$ 2.0 cm. In the present study, the performance of an industrial SPECT was evaluated by varying the number of detectors from 4 to 13 and 4 to 20 for 40 cm and 60 cm diameter columns, respectively (figure 2). The column is comprised of the water (1 g/cm^3) and the acryl wall (1.2 g/cm^3) of 1 cm thickness.

The radioisotopes of ^{99m}Tc (140 keV), ^{68}Ga (511 keV), and ^{137}Cs (662 keV) were placed at the center of the column in the simulations as a point source. The radiation detection system was assumed to use an energy window which was set to be ±10% of γ-ray energy released from the sources to discriminate scattered radiation [6]. In the simulation, the energy resolution of the detectors was assumed to be 22%, 11%, and 10% at 140 keV, 511 keV, and 662 keV, respectively, following the energy resolution of our detectors. The detection efficiency of the detector after applying energy window was 38%, 9%, and 5% for ^{99m}Tc (140 keV), ^{68}Ga (511 keV), and ^{137}Cs (662 keV), respectively. The energy response was considered to be Gaussian. The number of photons transported in the Monte Carlo simulations was 10^9 for each simulation case, which roughly corresponds to a 30-second measurement of a 1 mCi source for the sources considered in the present study. The SPECT images were reconstructed with the maximum-likelihood expectation-maximization (ML-EM) algorithm, and the spatial resolution of the reconstructed images was then determined from the profile at the center [7, 8].

3 Results

Figure 3 shows the reconstructed images and corresponding image profile at y = 0 for the 40 cm diameter cylindrical column. The image reconstruction value is divided by the maximum value of each image. The position of the peaks in image profile implies the reproduced source position, and therefore, multiple-peaks mean that the image has not adequately been reproduced for the point source simulated in the study. For ^{99m}Tc, the reconstructed image of 4 detectors (i.e., an industrial SPECT composed of detector arrays with 4 detectors) does not clearly reproduce the point source; however, the reconstructed images of 11 and 13 detectors reproduce the point source very accurately. For ^{68}Ga and ^{137}Cs, the reconstructed images of 4 detectors show a very low imaging resolution, but these images at least indicate the source location very well. The images are better for ^{68}Ga and ^{137}Cs than ^{99m}Tc for a relatively smaller number of detectors, which is due to higher counting efficiencies for ^{68}Ga and ^{137}Cs than ^{99m}Tc. Note that ^{68}Ga and ^{137}Cs emit more penetrative gamma-rays than ^{99m}Tc.

On the other hand, the FWHM of the profile of ^{99m}Tc is better than those of ^{68}Ga and ^{137}Cs when a sufficient number of detectors are engaged. This is principally due to the fact that fewer scattered photons contribute to the image reconstruction process for ^{99m}Tc because Compton scattering is more dominant at high photon energies compared to low photon energies.

Figure 4 shows the results for the 60 cm diameter column. For ^{99m}Tc, the reconstructed images do not adequately reproduce the point source, regardless of the number of detectors. This is mainly due to the fact that the low-energy gammas from ^{99m}Tc are not penetrative enough for the 60 cm diameter column. ^{68}Ga and ^{137}Cs show much better images than ^{99m}Tc, and the results of 15 and 20 detectors show acceptable resolutions.

Figure 5 shows the FWHM of the profile as a function of the number of detectors (for each detector array) for 40 cm and 60 cm diameter columns. The FWHM of the profile was calculated at y = 0. The results show that at least 8 and 11 detectors are needed for ^{99m}Tc and ^{68}Ga (and ^{137}Cs), respectively, to achieve a 4 cm spatial resolution which corresponds to 10% of the column diameter (= 40 cm). The results also show that at least 9 and 12 detectors are needed for ^{68}Ga and ^{137}Cs, respectively, to achieve a 6 cm spatial resolution which corresponds to 10% of the column diameter

2013 JINST 8 C04006

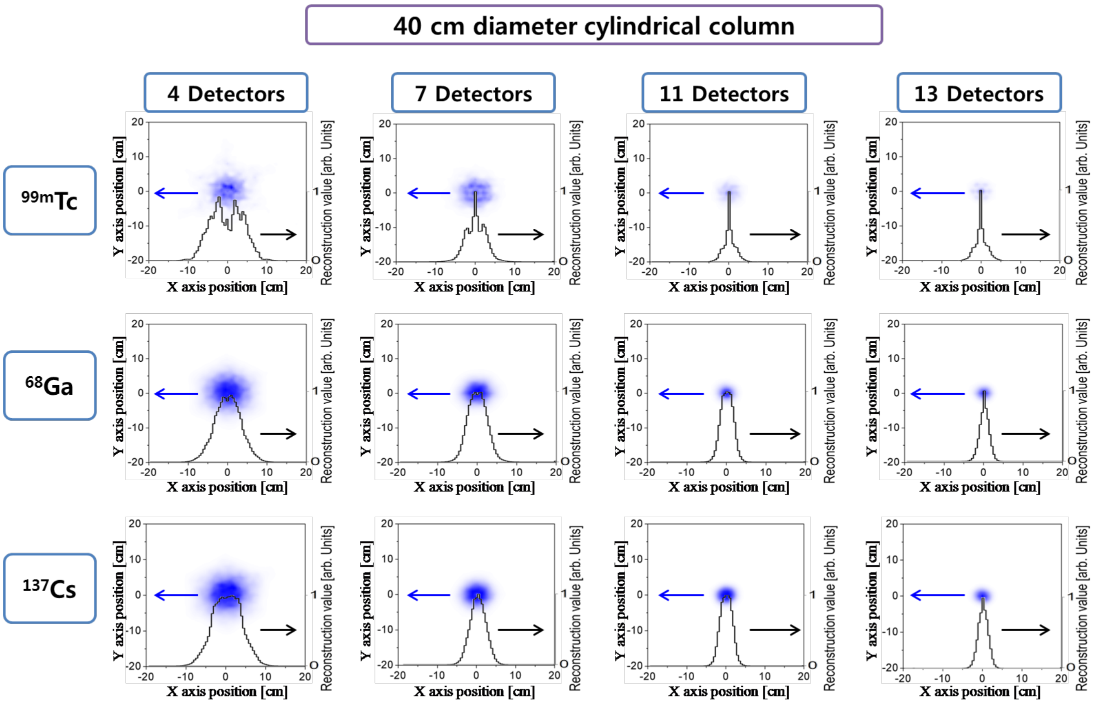

Figure 3. Reconstructed images (left hand side vertical axis and horizontal axis) and corresponding image profiles at y = 0 (right hand side vertical axis and horizontal axis) for the 40 cm diameter column.

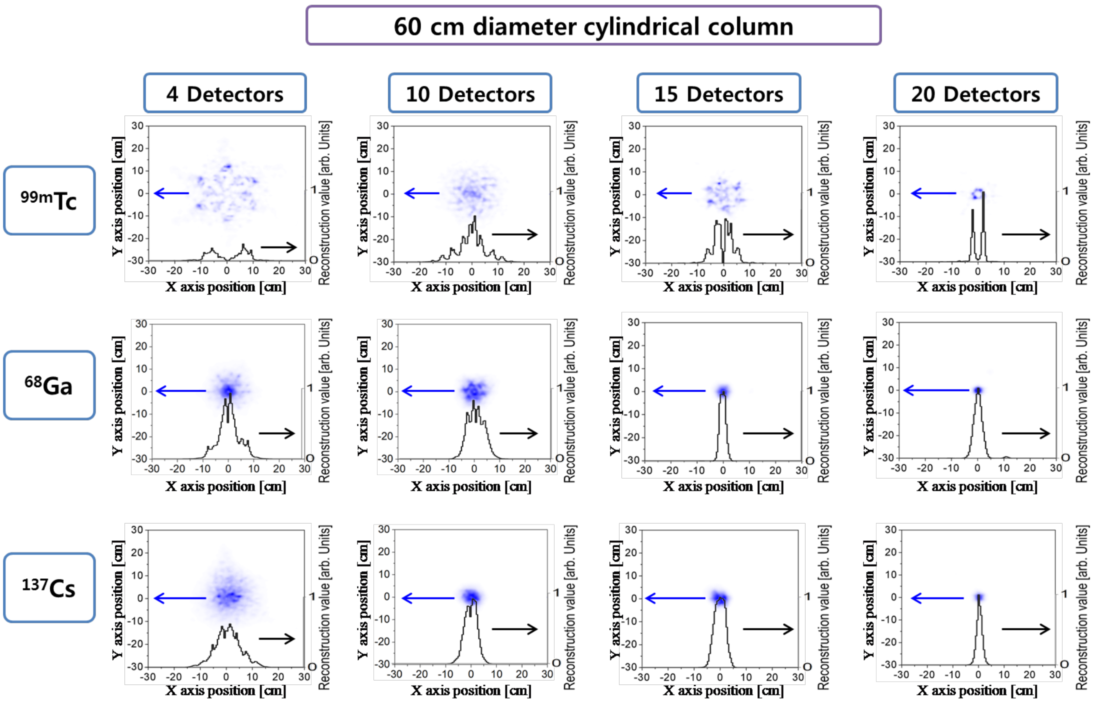

Figure 4. Reconstructed images (left hand side vertical axis and horizontal axis) and corresponding image profiles at y = 0 (right hand side vertical axis and horizontal axis) for the 60 cm diameter column.

2013 JINST 8 C04006

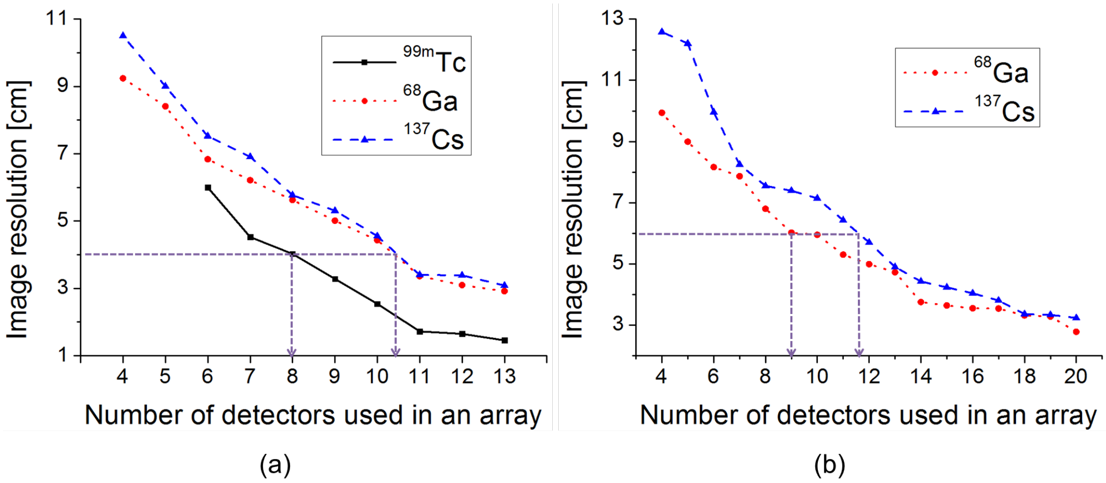

Figure 5. Calculated FWHM of the profile as a function of the number of detectors for the 40 cm diameter (a) and 60 cm diameter (b) columns.

(= 60 cm). For ^{99m}Tc, the industrial SPECT does not provide acceptable images for the large 60 cm diameter column, but provides a better imaging resolution for the small 40 cm diameter column than for ^{68}Ga and ^{137}Cs. This result emphasizes the importance of appropriate source selection considering the size of the imaging object. It is clearly advantageous to use low energy gamma sources for a small object and high energy gamma sources for a large object.

4 Conclusions

In the present study, a set of different geometries of industrial SPECTs were evaluated to determine the minimum number of detectors that will provide a spatial resolution that corresponds to 10% of the column diameter. Our results show that 11 and 12 detectors will satisfy the 10% resolution requirement for the 40 cm and 60 cm diameter columns, respectively, for the industrial SPECT and radioisotopes considered in the present study. The results of this study also emphasize the importance of appropriate source selection considering the size of the imaging object.

Futher study on the other structure of the industrial SPECT system will be carried out to improve performance of the industrial SPECT system, and as a result, the industrial SPECT will be utilized as the validation utility for computed fluid dynamic simulation in a multiphase reactor.

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2013 JINST 8 C04006

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