

Monte Carlo Simulation for the Design of Industrial Gamma-ray Transmission Tomography

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The Monte Carlo simulation and experiment were carried out for a large-scale industrial gamma ray tomographic scanning geometry. The geometry of the tomographic system has a moving source with 16 stationary detectors. This geometry is advantageous for the diagnosis of a large-scale industrial plant. The simulation data was carried out for the phantom with 32 views, 16 detectors, and a different energy bin. The simulation data was processed to be used for image reconstruction. Image reconstruction was performed by a Diagonally-Scaled Gradient-Ascent algorithm for simulation data. Experiments were conducted in a 78 cm diameter column filled with polypropylene grains. Sixteen 0.5-inch-thick and 1 inch long NaI(Tl) cylindrical detectors, and 20 mCi of ¹³⁷Cs radioactive source were used. The experimental results were compared to the simulation data. The experimental results were similar to Monte Carlo simulation results. This result showed that the Monte Carlo simulation is useful for predicting the result of the industrial gamma tomographic scan method And it can also give a solution for designing the industrial gamma tomography system and preparing the field experiment.

KEYWORDS: industrial process diagnosis, gamma tomography, Monte Carlo simulation, radioisotopes

I. Introduction

Industrial gamma-ray computed tomography systems are advantageous for diagnosing a large-scale plant because high energy gamma rays are more effective than X-rays in deep penetration. It can also be interpreted by equation (1) and **Fig. 1**. When incident rays with an intensity of I_0 and an attenuated ray of I are given, the mass thickness (μx) is determined as $\ln(I_0/I)$. Normally, I_0 can be measured for a long time and then averaged, and it is assumed as a constant with no statistical error. With this condition, the mass thickness with uncertainty can be dotted as equation (1) by the error propagation rule⁽¹⁾ as follows:

$$\overline{\mu x} \pm \sigma_{\mu x} = \ln(I_0 / I) \pm \sqrt{\frac{1}{I}} \quad (1)$$

where $\sigma_{\mu x}$ is the error of the mass thickness.

Fig. 1 shows that relative errors along the mass thickness when I_0 is 10,000 counts with gamma rays of 150 keV, 662 keV, and 1250keV. Each gamma ray has linear attenuation coefficients of 0.1505, 0.0862 and 0.0532 cm^{-1} in liquid water⁽²⁾. As seen in **Fig. 1**, high energy is effective for diagnosing a large-scale unit because fewer relative errors are shown as γ -ray energy increases.

Part of the γ -ray CT application field is noninvasive monitoring in chemical engineering.⁽⁸⁻⁹⁾ There have been many studies using gamma-ray tomographic methods for process diagnosis in chemical engineering. Gamma ray CT using 320 detector bins was developed for the study of a stirred chemical reactor.⁽⁶⁻⁷⁾ A BGO-based gamma-ray CT

was introduced and used for inspecting a lab-scale trickled bed reactor.⁽⁴⁻⁵⁾ Industrial gamma emission tomography was used for the visualization of radiotracer movement.⁽³⁾ Process visualization was achieved by using a gamma ray transmission or a gamma emission CT in these studies. Gamma ray transmission tomographic solutions give valuable information for the performance diagnosis of a fixed-bed reactor, packed bed column, and a bubble column, where phases do not abruptly change.

The development of a gamma ray CT system requires prior knowledge of the effect of design specifications such as source dimensions, activities, energies and detector types on the system. Trial-and-error method for the determination of a design specification takes time and is expensive when the system is large. The Monte Carlo simulation method can reduce the cost by giving the estimate of a result. Monte Carlo simulation methods have been widely used in many areas such as dose

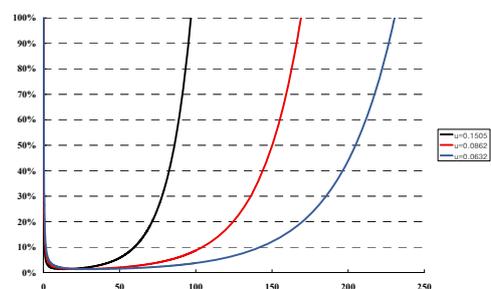


Fig. 1 Relative errors vs thickness (cm)

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assessment, shield and detector design. The Monte Carlo simulation method also can provide a solution for designing the industrial gamma tomography and preparing the field experiment. In this paper the Monte Carlo simulation results are presented for a specially designed geometry of a large-scale industrial scan and experimental result. The results for the geometry identical to the simulated one, are also presented.

2. Industrial tomographic scan method

Although there have been many case studies of gamma ray tomography systems used in laboratories and pilot plants, there are few real scale applications. In real-scale industrial plants, conventional tomographic scan methods could not be easily applied because of a limitation of space where platform, valves, ladders, and pipes are attached to plants. The scanning geometry in Fig. 2 was introduced in IAEA.¹⁰⁾ This scanning geometry has many advantages because a sealed radiation source is

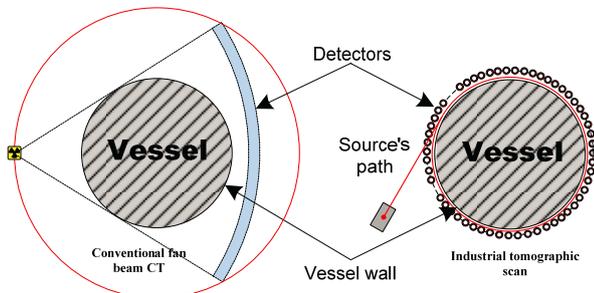


Fig. 2 The concept of the industrial tomographic scan method¹⁰⁾

usually small enough to travel through a guided tube as an NDT (Non Destructive Test) gamma source projector. Source moving and a stationary detection system are advantageous for avoiding a mechanical complexity. Instead of applying a conventional CT gantry to real scale industry, the same scan method as in Fig. 1 can be applied. A limited number of gamma ray detectors may result in low resolution data when it is compared to the conventional CT with high resolution array detectors. The resolution required for trouble-shooting depends on the size of defects that the plant engineers believe the cause a malfunction. High-resolution is required to find a small-sized mechanical defect, while a low resolution is sufficient for a large scale channeling of process media. Therefore the estimation of an output resolution for a given detection geometry is important to correctly choose the detection system for a given problem-solving situation. The Monte Carlo simulation method is suitable for this kind of evaluation. Fig. 3 shows the Monte Carlo simulation set up. Fig. 4 and Table. 1 show the detailed specifications of a source and detectors, respectively.

III. Monte Carlo Simulation

1. Selection of source and detector

Several factors such as activity, source dimension, and energy, can be evaluated for source specification. A source should be small enough to travel through a guided tube as an

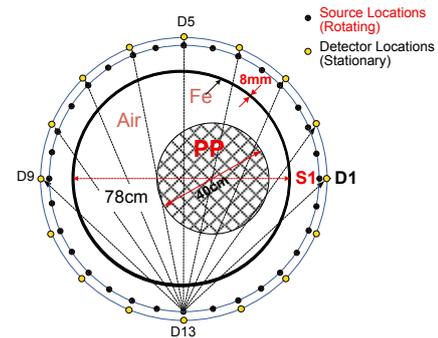


Fig. 3 Configuration of simulation setup

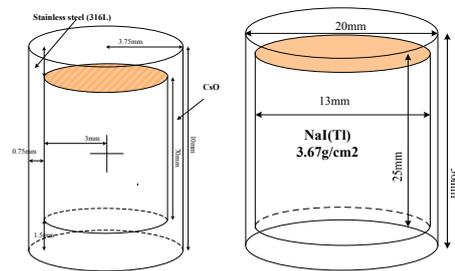


Fig. 4 Source and detector dimension

NDT irradiator. It should also emit radiation uniformly. The guided tube should not attenuate the radiation much. From these conditions, a cylindrical source and detector were preferred for the implementation for an industrial scanning geometry.

2. Blank-scanning data calculation

A tomography calculates the cross-section of the attenuation map by measuring incident photons and attenuated photons by object. For tomographic scan, attenuation data from all direction were required. A set of measurement data from detectors at one source position is called a view. Transmission scans with nothing but air in the scanning region is an “empty scan”.

Table. 1 Material information used for calculation

	Chemical form	Density(g/cm ³)
Detector	NaI	3.67
Detector shield	Al	2.7
Source active region	CsO	1.47
Source shield	Fe(70%),Mn,Cr	7.9
Vessel wall	Fe	7.9
Polypropylene(media)	CH ₂	0.6

Attenuation data and empty scan data are required for equation (2~3) at the same source and detector position as follows:

$$\mu x = \ln(I_i^0 / I) \quad (2)$$

In equation (2), I_i⁰ denote empty scan at i mode measurement. Fig. 5 shows the simulation result for empty scan data along the distance between the source and detector.

The measurement geometry was the same for I_i and I_i^0 . From a long-time simulation, an empty scan result with a low relative error was obtained.

3. Image reconstruction from simulation projection data

Statistical image reconstruction methods have known to be suitable for transmission measurements that have less scanned data.¹⁻²⁾ Equation (3) shows the DSGA algorithm¹⁾ which is one of the statistical image reconstruction methods, follows:

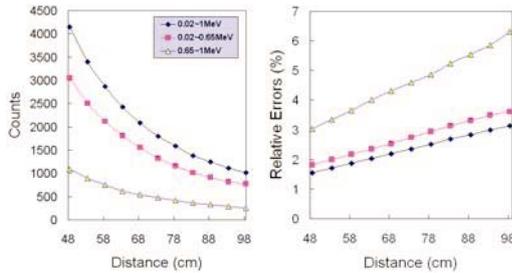


Fig. 5 Simulation at a variant S-D distance with different energy bins

$$f_j^{(n+1)} = f_j^{(n)} \frac{\sum_{i=1}^M (I_i e^{(-\sum_{k=1}^N h_{ik} f_k^{(n)})} \cdot h_{ij})}{\sum_{i=1}^M I_i \cdot h_{ij}} \quad 3)$$

Where f_j is the average linear attenuation coefficient in pixel j , h_{ij} is the length of the beam path i that intersects pixel j , and n is iteration number in equation (3). **Fig. 6** shows the mass thickness (μx) value calculated from detectors and its relative error at a source position by equation (1), which is a view at source position S1 (**Fig. 2**). Total simulation was

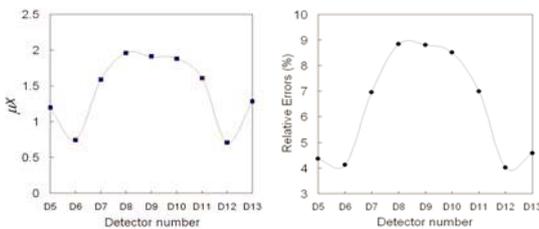
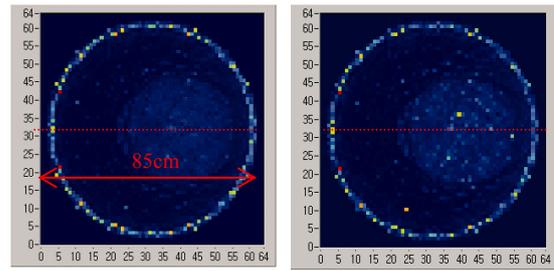


Fig. 6 μx calculation (Source location: S1, Detector locations: D5~D13, Energy bin:0~1 MeV)

carried out for 32 views and 16 detectors, which resulted in 512 items of data. But among the 16 detectors, 9~10 detectors were used for μx calculation at each view. So among the total 512 measurement data, 336 lay-sums were used for reconstruction. Image reconstruction result was calculated for the energy bin of 0~1 MeV and 0.02~1 MeV.



(0~1 MeV) (0.02~1 MeV)
Fig. 7 Reconstruction from simulation result

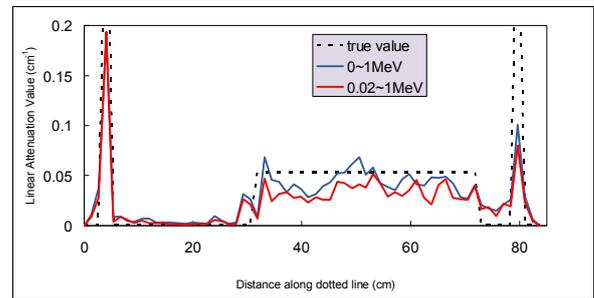
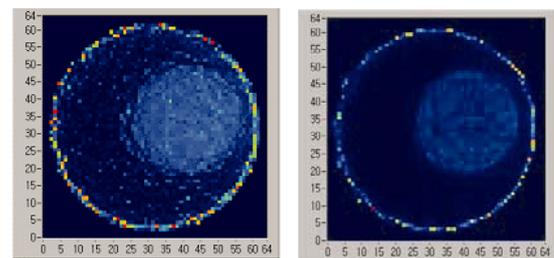


Fig. 8 Reconstructed linear attenuation value from **Fig.7**

Fig. 7 shows the reconstruction result displayed in a 64×64 grid for simulation data. In the display, a grid index of 0~64 is matched to 0~84 cm in a physical dimension. **Fig. 8** shows the linear attenuation of the reconstruction image along the dotted line of **Fig. 7**(left).

IV. Implementation and experimental results

The system was implemented with 16 detectors of 0.5×1 inch and 20 mCi of ^{137}Cs . Data was collected through the data



(32 views) (64 views)
Fig. 9 Experimental result

logger at the preset step with 5 sec recording time. The number of emitted photon is 100 times of photon histories which were used for simulation. The reconstructed result was showed in **Fig. 9**. The results were reconstructed from the experiment condition of 32 and 64 views. In order to take account of the threshold setting in an experiment, the simulation results were recorded in an energy bin of 0.02~1 MeV. From the comparison with the

experimental results with the 20mCi of ^{137}Cs , the predicted result showed a similar quality of image resolution with the case of the 32-view measurement.

V. Conclusion

The Monte Carlo simulation was successfully applied to predict the radiation detection results for an industrial gamma tomography system. It was demonstrated that the proposed scanning method can provide the image solution for a large-scale inspection where conventional technology cannot be applied. In an industrial tomographic scan, the object and measurement geometry have no specific patterns. This makes it difficult to get a prefixed design which is applied universally to the industrial unit. This means that each case has its own geometries and different combinations of sources and detectors. The optimal scanning condition depends on time and expenses for the expected output. For the optimal design of an industrial scanning system, a precise simulation is required. This can be an example of the application of the Monte Carlo simulation to the inspection industry. In spite of the rapid progress of the conventional inspection method, there are not many CT applications in real-scale inspections of petrochemical plants. The industrial tomographic scan method supported by the Monte Carlo simulation can be a solution for a real-scale process diagnosis.

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