Development of remaining wall thickness measurement system for boiler wall tube using gamma scattering technique

K Durongsak, C Yenjai, and S Rassame
Department of Nuclear Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, 10330 Thailand

1 Corresponding author e-mail: somboon.ra@chula.ac.th

Abstract. In this study, the General Monte Carlo N-Particle version 5 (MCNP5) simulation of the measuring system for the remaining thickness of the wall tube using gamma scattering technique is performed to investigate the applicability of this technique and to find the optimum geometrical setup for the experimental setup. The numerical results show that the optimal geometry condition to provide the highest ratio between the gamma flux changes per thickness variation, namely, the measurement sensitivity, is the alignment of the source incidence angle of 30 degree and detector scattering angle of 30 degrees. Sequentially, the preliminary experiment of thickness measurement system for the tube using the gamma scattering technique is conducted based on the selected geometrical test setup by the simulation. It is found that the experimental results have generally a good agreement with the calculated results. Conclusively, it is suggested that the gamma scattering technique has a potential method to measure the remaining wall thickness in the boiler wall tube.

1. Introduction

The wall tubes in boiler of the fossil-fired power plant are very essential component which function in heat transferring from the boiler combustion room into the water inside the tubes. The inspection of the remaining thickness of wall tubes is required to perform annually during the maintenance period of the plant. To estimate the remaining thickness of tube, several techniques can be used as the non-destructive testing methods such as the gamma radiography, thermograph, Eddy current, infrared thermograph, and Ultrasonic Testing (UT) technique. Among those techniques, the UT technique is quite more popular in the power plant industry due to several advantages such as its good accuracy and acceptable measuring cost. However, the disadvantages of the UT technique are the long-time measuring and the need of professional skills in the UT.

The applicability of gamma scattering techniques in the tubes or pipes thickness measuring has been investigated by several researchers. For instance, Abdul-Majid and Tayyeb tried to measure the difference thickness of the carbon tubes at 100, 160, and 200 mm thick tubes with 50 mm of the covered insulation by the gamma ray scatterings using the setting the Cs-137 radioisotope source, the radiation at 10 mCi, and 2”×2” NaI(Tl) detector [1]. The test results from his study shows that the tube should be less than 10 mm in thickness in order to be measure the tube thickness accurately.

In addition, Abdul-Majid and Balamesh [2] used the gamma ray scatterings to measure the iron carbon tube 280 mm diameter, thickness with 9 mm and 40 mm asbestos covered with the insulation. They applied gamma ray from 5 mCi Cs-137 radioisotope source with 7 mm collimator. The backscattered radiation was measured by 2”×2” NaI(Tl) detector connected with multichannel
analyzer. The test results found that the system could analyze defect at the tubes about 70 mm in diameter. Also, Abdul-Majid and Balamesh [3] studied the measuring system installed into the waterproof pipe for the underwater test. The signal was transferred via 100 m cable line. The backscattered radiation was measured by 2”×2” NaI(Tl) detector connected with multichannel analyzer. The results of his study indicated that the amount of backscattered radiation depended on the tube’s thickness.

Moreover, Vo Hoang Nguyen et al. [4] simulated the thickness measurement of pipe-wall by gamma scattering technique using the MCNP4C codes and Geant4. The related experiments were conducted to investigate the correction of the simulation results. The purpose of this study is preliminary investigating the applicability of gamma scattering technique to the weared thickness of wall tube measurement system. The investigation result will also determine the optimum geometrical setup condition for the system. The MCNP5 code is applied to simulate the system. The sensitivity of the scattered gamma flux change due to the thickness change is calculated in several geometrical set-ups with the relevant angles conditions. The experiments are performed in accordance with the selected test conditions in order to verify and validate the numerical results.

2. The gamma scattering technique

Figure 1 shows the schematic diagram of the thickness measurement using the gamma scattering technique. The radiation source is placed in the collimator at a possible angle (0°-180°) to the radiation detector respected to the plane of workpiece. This technique is applicable to measure the thickness of one-side tube thickness or the tube that the radiation source or the radiation detector cannot put conveniently inside the tube.

\[
\frac{h\nu'}{1+ \frac{h\nu}{m_0c^2} [1-\cos \theta]} = h\nu
\]

\( h\nu' \) is the energy of the scattered gamma ray
\( h\nu \) is the energy of gamma ray reflected on the workpiece
\( m_0c^2 \) is rest mass energy that is 0.511 MeV
\( \theta \) is the scattering angle

The equation (1) obviously indicates that the energy of Compton scattered gamma ray depends on the energy of gamma ray interacted to the workpiece and the scattering angle of gamma ray. In order to estimate the workpiece’s thicknesses (T), the equation (2) can be used [4]:

Figure 1. Set up for gamma scattering.
\[ T = -\frac{1}{\mu_{\text{eff}}} \ln \left( 1 - \frac{I}{I_s} \right) \] (2)

I is the intensity of scattered gamma ray
I_s is the constant intensity of scattered gamma ray at saturation thickness of workpiece
\( \mu_{\text{eff}} \) is the linear absorption coefficient of the workpiece

It is noted that the equation (2) is developed based on the workpiece which has a shape in planar. It should be verified further if the equation directly applicable to the tube thickness estimation.

3. Simulation and experiment

3.1. MCNP Simulation

The General Monte Carlo N-Particle code developed by Los Alamos National Laboratory is a general-purpose code that has widely used to simulate the coupled neutron, photon, and electron transport problem [6]. It has a capability to simulate a variety of nuclear particles with flexible geometry and materials used in samples or detectors. In this study, the MCNP version 5 (MCNP5) is used to simulate wall thickness measurement system of boiler tubes using gamma scattering technique.

![Figure 2. Set-up geometry of measurement in the MCNP5 simulation.](image)

Figure 2 displays the geometry model for the thickness measurement system in the MCNP5 simulation. In the MCNP simulation, a gamma source, a shielding cylinder, a NaI(Tl) detector, and a wall tube are key modelled components using the MCNP5 code.

The scintillation crystal of NaI(Tl) detector is a cylinder with diameter of 5.08 cm and length of 5.08 cm. The detector is shielded by the lead cylinder with length, inner diameter, and outer diameter of 20.08 cm, 5.08 cm, and 7.08 cm, respectively.

A Cs-137 radioactive source emitting 661.6 keV of gamma ray energy is used in this simulation. The gamma source is specified as the point source which contain inside the cavity of a cylindrical copper with length of 7 cm and diameter of 5 cm. Gamma ray emitted from the source are collimated by a lead cylindrical collimator with length, inner diameter, and outer diameter of 12 cm, 1 cm, and 15 cm, respectively.

The wall tubes used in the experiment are made of carbon steel with the content of each element as follows: Fe: 99.60%, Mn: 0.93% C: 0.27% Si: 0.10%, K: 0.035%, S: 0.035%, Cr: <0.01%, Mo: <0.01%, and Ni: <0.01%. Five different thicknesses of wall tubes were prepared with remaining thicknesses of 1, 2, 3, 4, and 5 mm. All tube samples have inner diameter of tube is 4.08 cm, outer diameter is 5.08 cm, and length is 100 mm.

The distance from the surface of the source collimator to the surface of the wall tube was maintained at 15 cm and the distance from the surface of the NaI(Tl) detector to the surface of the wall tube was set at 15 cm.
In the MCNP5 simulation, the calculated conditions with the varied incidence and scattering angles are showed in the table 1. For each calculated condition, the simulation is performed with the wall tube thickness of 1, 2, 3, 4, and 5 mm. Energy distribution of scattering gamma created in a detector is calculated using the F8 tallies in the MCNP5. The intensity at area of the scattering peak will be subtracted with the intensity at area of the Compton scattering from the detector.

Based on the MCNP5 calculated results, the total area of single scattering peak at each thickness values is estimated and the relationship between the intensity of single scattering peak and the thickness of wall tube are gained. The sensitivity of the thickness measurement system is estimated by the slope of graph showing the relation of the intensity of single scattering and thickness of wall tube.

Table 1. Calculated conditions in the MCNP5 simulation.

| Calculated condition No. | Incidence angle (degree) | Scattering angle (degree) | Calculated condition No. | Incidence angle (degree) | Scattering angle (degree) |
|------------------------|-------------------------|--------------------------|------------------------|-------------------------|--------------------------|
| 1                      | 0                       | 60                       | 15                     | 30                      | 50                       |
| 2                      | 0                       | 70                       | 16                     | 30                      | 60                       |
| 3                      | 0                       | 80                       | 17                     | 40                      | 20                       |
| 4                      | 0                       | 90                       | 18                     | 40                      | 30                       |
| 5                      | 10                      | 50                       | 19                     | 40                      | 40                       |
| 6                      | 10                      | 60                       | 20                     | 40                      | 50                       |
| 7                      | 10                      | 70                       | 21                     | 50                      | 10                       |
| 8                      | 10                      | 80                       | 22                     | 50                      | 20                       |
| 9                      | 20                      | 40                       | 23                     | 50                      | 30                       |
| 10                     | 20                      | 50                       | 24                     | 50                      | 40                       |
| 11                     | 20                      | 60                       | 25                     | 60                      | 0                        |
| 12                     | 20                      | 70                       | 26                     | 60                      | 10                       |
| 13                     | 30                      | 30                       | 27                     | 60                      | 20                       |
| 14                     | 30                      | 40                       | 28                     | 60                      | 30                       |

3.2. Experiments

3.2.1. Wall tube. The wall tubes used in the experiment are made of carbon steel. The composition of this material is identical to an actual wall tube used in boiler of a coal-fired power plant. Five samples of wall tubes with the different remaining thicknesses of 1, 2, 3, 4, and 5 mm were prepared in order to find the relation between the intensity of single scattering and remaining thickness of wall tubes. Figure 3 shows the photographs of wall tube samples used in the experiment.

![Figure 3. Remaining thickness of wall tube (a) 1 mm (b) 2 mm (c) 3 mm (d) 4 mm (e) 5 mm.](image)

3.2.2. Experiment set-up and performing. The dimension of detector, detector shielding, radiation source and source collimator and shielding including their materials used and the equipment arrangement are identical to what are specified in the MCNP5 simulation. The experiments used the 5.08 cm × 5.08 cm NaI(Tl) detector that consists of the photo multiplier at the end and shielded by lead cylinder in one side. Another ended side of detector was connected to the tube base that serves as signal amplifier. The measured signal was transferred to the computer and display as a gamma spectrum. The experiments used 0.1 mCi of Cs-137 radiation source which contained in a lead
shielding and collimator. Experimental set-up is illustrated in the figure 4. To verify the calculated results of the MCNP5 calculation, some experiments at the selected condition are three of the best performed. The intensity of the single scattering peak at the each thickness of wall tube is estimated based on the measured results in each condition.

**Figure 4.** Experimental set-up for remaining thickness measurement of a wall tube.

4. Results and Discussion

4.1. Analysis of simulation’s results

Figure 5 show the geometries modelling of experiment using in MCNP5 which demonstrates the gamma ray scattering in the simulation. It is clearly shown in the MCNP5 displaying program that some gamma rays enter directly to the detector without the scattering to the tube consequently, the Compton scattering occurred in detector without scattering play some roles to the measurement. Therefore, the intensity at area of the gamma scattering peak in the detector is necessary to subtract with the intensity at area of the Compton scattering from the gamma ray directly to the detector.

**Figure 5.** Example of particles displaying by MCNP5.

**Figure 6.** An example of MCNP5 simulation scattering and background spectra with a 3 mm remaining thickness of wall tube at the calculated condition no. 13.
Table 2. Sensitivity estimated by the MCNP5 calculated results.

| Calculated condition No. | Incidence angle (degree) | Scattering angle (degree) | Sensitivity (count/mm) |
|--------------------------|--------------------------|---------------------------|------------------------|
| 1                        | 0                        | 60                        | 16,752                 |
| 2                        | 0                        | 70                        | 15,024                 |
| 3                        | 0                        | 80                        | 15,242                 |
| 4                        | 0                        | 90                        | 15,218                 |
| 5                        | 10                       | 50                        | 16,444                 |
| 6                        | 10                       | 60                        | 15,024                 |
| 7                        | 10                       | 70                        | 15,126                 |
| 8                        | 10                       | 80                        | 15,798                 |
| 9                        | 20                       | 40                        | 15,548                 |
| 10                       | 20                       | 50                        | 15,940                 |
| 11                       | 20                       | 60                        | 16,544                 |
| 12                       | 20                       | 70                        | 15,940                 |
| 13                       | 30                       | 30                        | 19,434                 |
| 14                       | 30                       | 40                        | 16,668                 |

The sensitivity (count/mm) is estimated by the slope of graph showing the relation of the intensity of single scattering and thickness of wall tube. Based on the calculated results shown in the table 2, it is concluded that the calculated condition no. 1, 13, and 25 are the top three conditions that provide the highest value of the sensitivity. These three conditions of incidence angles and scattering angles according to the calculated condition no. 1, 13, and 25 are selected to perform the tests to validate the calculation results by the MCNP5 simulation.

4.2. Comparison between experimental and calculated results
Table 3 shows the comparison between the intensity of the single scattering peak obtained from the experiment and estimated by the MCNP5 simulation. It can be seen that the calculated and experimental results are good agreement. Additionally, it is seen that the intensity of the single scattering peak is higher with thickness increasing in both of the experimental and calculated results.

A scattering spectrum of 662 keV gamma photon beam scattered on a 3 mm remaining thickness of wall tube obtained by experiment and simulation are shown in the figure 7. The energy position of single scattering peak in the experimental and simulated results is closed to approximately 210 keV which is the $E'$ the scattered gamma ray calculated by the equation (1).

Table 3. Area of single scattering peak obtained from experiment and simulation of condition no. 1, 13 and 25.

| Condition No. | Incidence angle (degree) | Scattering Angle (degree) | Thickness of wall tube (mm) | Area of single scattering peak (counts) | Experiment | MCNP5 | % Relative |
|---------------|--------------------------|---------------------------|-----------------------------|----------------------------------------|------------|-------|------------|
| 1             | 0                        | 60                        | 1                           | 145,789                                | 132,180    | 90.67 |
| 2             | 0                        | 70                        | 2                           | 165,892                                | 153,240    | 92.37 |
| 3             | 0                        | 80                        | 3                           | 180,546                                | 170,100    | 94.21 |
| 4             | 0                        | 90                        | 4                           | 193,648                                | 182,400    | 94.19 |
| 5             | 10                       | 50                        | 5                           | 202,445                                | 191,280    | 94.48 |
| 13            | 30                       | 30                        | 1                           | 178,860                                | 133,740    | 74.77 |
| 14            | 30                       | 40                        | 2                           | 196,542                                | 154,680    | 78.70 |
| 25            | 60                       | 0                         | 3                           | 215,350                                | 174,240    | 80.91 |
|               |                          |                            | 4                           | 234,791                                | 192,000    | 81.77 |
|               |                          |                            | 5                           | 245,132                                | 202,680    | 82.68 |
|               |                          |                            | 1                           | 168,945                                | 162,120    | 95.96 |
|               |                          |                            | 2                           | 184,243                                | 182,160    | 98.87 |
|               |                          |                            | 3                           | 201,544                                | 198,720    | 98.50 |
|               |                          |                            | 4                           | 217,689                                | 214,260    | 98.42 |
|               |                          |                            | 5                           | 220,144                                | 219,960    | 99.92 |
Table 4 shows the sensitivity obtained by the experimental results and the MCNP5 calculation at the condition no. 1, 13, and 25. Among those three conditions of the related angles, the maximum sensitivity is found to be 19,434 and 18,660 counts/mm in the simulation and experiment, respectively, at the condition no. 13 of 30 degree of incidence angle and 30 degree of scattering angle.

Figure 8 shows an example of the intensity of single scattered photon and the remaining thickness of wall tube in the condition no. 13. It can be seen that the similar trend on the changing of intensity of single scattering peak area with the remaining wall tube thickness is found. It is noted again that the sensitivity of measurement is estimated by the slope of graph. For the condition no. 13, the sensitivity of 19,434 and 18,660 counts/mm are obtained in the MCNP5 calculation and experiment, respectively.

**Figure 7.** An example of scattering spectrum of 662 keV gamma photon beam scattered on a 3 mm remaining thickness of wall tube by experiment and simulation in the condition no. 13.

**Figure 8.** Intensity of single scattered photon and remaining thickness of wall tube in the condition no. 13.
Table 4. An example data of sensitivity obtained by experiments and simulations.

| Condition No. | Incidence angle (degree) | Scattering angle (degree) | Sensitivity (counts/mm) | Experiment | MCNP5 | % Relative |
|---------------|-------------------------|---------------------------|-------------------------|------------|-------|-----------|
| 1             | 0                       | 60                        | 15,823                  | 16,752     |       | 94.45 %   |
| 13            | 30                      | 30                        | 18,660                  | 19,434     |       | 96.02 %   |
| 25            | 60                      | 0                         | 16,398                  | 17,298     |       | 94.80 %   |

5. Conclusion
The MCNP5 code is applied to simulate the measuring system for the remaining thickness of the wall tube using gamma scattering technique. The alignment of radiation source and detector setup as well as the tube remaining thickness is varied as input parameters in the MCNP calculation. Three conditions of the measure equipment alignment providing the highest values of measurement sensitivity are selected to perform the experiment in order to confirm the validity of numerical results. It is found that the relation between the intensity of the single scattering peak and the tube remaining thickness obtained by the experiment and MCNP calculation has well correlated. The alignment of the source incidence angle of 30 degree and detector scattering angle of 30 degrees are considered as the best geometric set-up to provide the highest measurement sensitivity at approximately 19,434 and 18,660 counts/mm. It is suggested that the measuring system using gamma scattering technique has a potential to use as the alternative technique in wall tube remaining thickness measurement but the detailed analysis may require for further improvement the accuracy of the measurement system.

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