Gamma ray thickness measurement

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Abstract. Gamma ray attenuation coefficients are different in diverse condition after its penetration through different components. This character has been widely used in worldwide researches for kinds of measurement treatments in medicine, and industrial detection etc. This study is mainly about one of applications of gamma ray measurement which is called gamma ray thickness measurement. Moreover, this paper also introduces principles of gamma ray detection methods and attenuation principles as well as digging its best measurement condition of the correlations. Continually, the paper will state a derivation process of the best condition by calculations.

1. INTRODUCTION

In industry and research, thickness measurements are the basic step before operations, which have been widely developed in the various fields, such as metal material testing, mechanic assembly. For instance, in medical field, Rabbi et al. [1] use COMSOL Multiphysics software to build the model of the muscle and fat to do the research. They measure the thickness of obese by electrical impedance myography. In geophysics filed, Prantner [2] use electric resistivity tomography, Ground Penetrating Radar and Refraction Seismics to measure the thickness of ice. In recent years, various approaches have been developed for thickness metering the electrical impedance, gamma radiation attenuation, microwave, and optical approaches[3]. Optical techniques are confined to the transparency of the mediums, and the light penetrability is enslaved to material transparencies. Electrical probes have been widely commercially available due to the economics and convenience characteristics. However, Electrical methods are temperature dependent, which need careful calibration to meet the requirements of online thickness measurement. Moreover, electrical probes suffer from temperature drift problems, which may result in a significant shift in the calibration and thus a loss of sensitivity. The gamma ray stands out among these methods because of its accuracy, good penetration and non-intrusive characteristics [4].

Extensive thickness measurement studies have been conducted for different purposes. Bessinger et al. [5] have given a formula which is similar to the formula in the following experimental principles:

\[ I = I_0 e^{-\mu t} \]

This formula uses the most important character of the gamma ray which shows the correlation of intensity and gamma ray attenuation. Pan et al. [6] did the research on measurements of horizontal high-pressure wet gas flow based on gamma-ray techniques. This study also uses the character of the attenuation. In other fields, Kladny et al. [7] studied magnetic resonance method of bones thickness measurement in medicine which is effective in measuring.
In our experiment, we aim to validate the accuracy of the gamma ray thickness measurement. Gamma ray which owns penetrability and law of attenuation is used to rip in different thickness. This experiment only refers single-phase flows. In this experiment, we use PVC plates as a solid phase to detect the change of gamma ray from an initial condition to received condition. Then we analyzing the change of the intensity of the gamma ray in order to reckon the change of the thickness of the plates. By measure the intensity of the standard and unknown PVC plates to reckon the result. We also do analysis for the data as well as analyzing the usability and accuracy of the gamma ray method.

According to results, we do a comprehensive analysis of errors and dig the forming equation of the best testing condition.

2. MEASUREMENT METHODS AND PRINCIPLES

2.1. Gamma ray thickness measurement principles

As the narrow-beam gamma ray penetrates materials, the attenuation of the intensity of ray obeys exponential decay law.

The law is concluded as a general formula:

\[ I = I_0 e^{-\mu \rho d} \]  (1)

where, \( I \) is the intensity of rays after penetration; \( I_0 \) is the initial intensity; \( \mu \) is the coefficient of the attenuation of the quality of rays; \( \rho \) is the density of the material; \( d \) is the thickness of the material.

While \( I_0 \) and \( I \) can be detected, the coefficient of the attenuation of the quality of rays is changeless for the homogeneous substance. Conclusively, we could function the formula to calculate the thickness.

There are three main effects of gamma ray and substance: photoelectric effect, Compton effect and electron pair effect. When the energy of the gamma photon is lower (less than dozen of keV), the cross section for the photoelectric effect is larger, it plays a major role of the quality attenuation coefficient. When the gamma ray energy is between 100keV and MeV, The Compton effect plays a major role in the mass attenuation coefficient while the electron pair effect plays a major role over a few MeV energy.

Figure 1 shows that the coefficient of quality attenuation of elements changes due to different energy of rays. We can easily find out that coefficients of other elements are obviously close except element H from Fig. 1. From Eq. (1), this phenomenon is reasonably beneficial to thickness measurement because the proportion of components of measured substance will lightly fluctuate, which will affect the results of measurement. If coefficients are closer, the influence of the result will be lower.

In addition, 662keV gamma ray energy is fitter for measuring the material with bigger thickness since its lower coefficient (stronger penetrability). Oppositely, we should use gamma ray with lower energy to measure thinner substance, such as 60keV gamma ray of Am-241. Eq. (2) could be used to judge where thickness measurement has the best sensitivity.

\[ \mu \rho d = 1 \]  (2)

Fig. 1 Correlation between quality attenuation coefficient and photon energy of several elements
2.2. Gamma ray detection

Commonly used gamma detectors include gas detectors, scintillation detectors and semiconductor detectors. Common gamma detectors include gas detectors, scintillation detectors and semiconductor detectors. In spite of its low energy resolution, scintillation detectors own characters of high detective efficiency, low cost, and high reliability which make it widely used in industrial measurement. NaI (TI) detector is one of the most frequently-used detectors which has better energy resolution why we use it in this experiment.

NaI detector working processes are as follows: First, the gamma photons are incident to NaI crystals and have effects with NaI crystals which produce light. Then the light will be absorbed by a photomultiplier tube (PMT) as well as switched into electrical signals. Electrical signals will be enlarged and transported to the data processing circuit. In addition, magnification of PMT is related to high voltage supplied which means that we can change numeral value of high voltage to change the magnification.

When the NaI detector carries out gamma photon measurement, it can be divided into two ways according to the amplitude of the output signal. One is the linear relation between the amplitude of the output signal and the photon energy, which can be used in the energy spectrum analysis. The second is that the amplitude of the output signal cannot reflect the photon energy information, only records the count of the output pulse and reacts the intensity of the ray by counting. In this experiment, since the thickness measurement only needs ray intensity, second ways are adopted. The system structure of the experimental device is shown in Fig 2. Each part is emphasized by different colors in the picture.

![Fig. 2 Schematic of the system structures and the experimental devices](image)

In order to make the detection system work steadily, it is necessary to measure the plateau characteristic curve of the detector, that is to change the high pressure of the photomultiplier tube, measure the count of the ray, and draw the curve of the counting with the high pressure when the radiation intensity of the detector is fixed. Working high pressure is selected in the area of counting with the gentle change of the high pressure. This can reduce the influence of high pressure change on the measurement count. See the diagram of the plateau characteristic curve (Fig 3). According to the plateau characteristic of the gamma ray detector, 1000V was selected as the working voltage of the photomultiplier tube.

![Fig. 3 The plateau characteristic curve](image)
2.3. Thickness measurement calibration
The formula for thickness measurement can be derived from the Eq. (1):

\[ d = -\frac{\ln I}{\mu p} + \frac{\ln I_0}{\mu p} \] (3)

There are two schemes to determine these parameters.

Scheme one: Measure I0 directly by the detector. I check the coefficient of the quality attenuation from the form according to the elementary composition of the measured material. The density can also be determined by actual measurement. In practical applications, it is inconvenient in practical applications. The calculation of mass attenuation coefficient will lead to larger errors.

Scheme two: I0, \( \mu \), and \( \rho \) are constant for stationary materials. Therefore, the thickness measurement Eq. (3) can be changed to:

\[ d = A \cdot \ln I + B \] (4)

In the calibration experiment, a set of materials with known thickness are used to measure, and a group of (thickness, ray counts) is measured and the number of ray counts is taken. So, the A and B parameters can be calibrated by using the linear least square fitting of Eq. (4). We adopted the second scheme because its the calibration accuracy and convenience in practical application. Put the sample to be measured on the ray beam, and then measured the intensity I of the ray that has penetrated the sample. Thickness can be measured according to the calibrated thickness calculation Eq. (4).

3. EXPERIMENTAL DEVICE AND STEPS

Figure 3 shows the basic structure of the whole device and the inside structure of the radiation source. The inside structure includes leaden isolation surrounding the core and aluminum top isolation plate, radioactive resource. The most important part is the radioactive source which consists of Cesium 137 (with 10 mCi activity) and Americium 241 (with 100 mCi activity).

Firstly, we needed to ensure the best voltage to operate the experiment. So, we tested the count of each voltage for one minute and record it in a form. The voltage ranges from 500V to 1200V while the common difference is 50V. Then we fitted the plateau curve as well as finding the smoothest part of the curve to determine the best voltage.

Then, we should calibrate the instrument and draw the thickness-intensity curve. Later, we measured the thickness of 7 PVC standard plates and record the data, orderly put 7 plates on the gamma radiation instrument. We continually did the measurement and recorded the count rate in the condition of setting 7 plates. We repeated the last steps after taking a plate away for 6 times. Then we did the data processing and made a form to fit the thickness-intensity as well as getting equations of the linear and polynomial trend lines for the following calculation.

Continually, we measured the unknown thin and thick plates, recording the data of unknown PVC plates in two conditions. One was testing it alone. Another was to test it above 3 PVC standard plates. Each measurement period lasted 10 minutes. Then we brought the data to the equations that mentioned in step 2 to calculate the actual thickness. Next, we could easily calculate the errors in each situation.

Moreover, we still had to do the mathematical deduction to testify the usability of the method.
4. EXPERIMENT RESULTS

Figure 5 and 6 are the linear and polynomial fit curve of Intensity-Thickness curve.

The fitting curve formulas are:

Linear:

\[
\begin{align*}
d &= -11.33945 \ln I + 108.76503 \\
\text{Polynomial:} & \quad d = -11.33945 \ln I + 108.76503 - 3
\end{align*}
\]  

The thickness of the thin plate is calculated when the thin plate is measured separately (according to Eq. (5) and (7))

Linear: \(d=0.503\text{cm}\)

Polynomial: \(d=0.512\text{cm}\)

The thin plate is measured with three standard plates, the thickness of the thin plate is calculated as follows (according to Eq. (6) and (8))

Linear: \(d=0.489\text{cm}\)

Polynomial: \(d=0.485\text{cm}\)

The thickness of the thick plate is calculated when the thin plate is measured separately (according to Eq. (5) and (7))

Linear: \(d=1.508\text{ cm}\)

Polynomial: \(d=1.511\text{ cm}\)

The thick plate is measured with three standard plates, the thickness of the thin plate is calculated as follows (according to Eq. (6) and (8))

Linear: \(d=1.481\text{ cm}\)
The sources of error in measurement are mainly the statistical fluctuations in counting time, but when the count is very high, the influence of statistical fluctuation is relatively small. In addition, there will be some physical gaps between the plate and the plate when it is measured, which cannot be eliminated, resulting in the impact on the measurement results. The same material cannot be exactly the same in different positions. When the plate is taken, it may be the wrong position of the measuring position, resulting in a certain error.

The errors in this experiment are basically under 5.00% that could be accepted in the physics experiment. The accuracy of measurement is in reasonably high standard which could be frequently used in the study.

4.1. Formula analyses
In the previous discussion about the best measurement condition, we determine that the result of measurement will be most accurate when the variables reaches the condition:

\[ \mu \rho d = 1 \]

The reason why it could be the best condition is calculated and we have to do the explanation of the final conclusion through the basic mathematical operation.

Firstly, we transform the Eq. (1) into the following form:

\[ \mu = -\frac{\ln \left( \frac{I}{I_0} \right)}{\rho d} \]  (9)

According to original formula, we can reckon a derivation formula:

\[ I' = I_0 e^{-\mu \rho_0 d_0} \]  (10)

\[ I = I_0 e^{-(\mu d + \mu \rho_0 d_0)} \]  (11)

where, \( I' \) and \( I \) are the intensities in the calibration experiment and formal experiment. \( \mu_0, \rho_0, \) and \( d_0 \) are the variables in the condition of air.

On the basis of definition of \( I \), we summarize the formula of uncertainty:

\[ I = \frac{E}{\tau} \]  (12)

\[ \Delta I = \frac{I}{\sqrt{\tau}} \]  (13)

In addition, the uncertainty of \( I' \) is 0 since the \( \mu_0, \rho_0, \) and \( d_0 \) are the stationary variables.

Then we calculate the uncertainty of \( \mu \) through the Eq. (12):

\[ \Delta \mu = \frac{1}{\mu d} \sqrt{\left( \frac{\partial \mu}{\partial I'} \right)^2 \Delta (I')^2 + \left( \frac{\partial \mu}{\partial \mu} \right)^2 \Delta \mu} \]  (14)

Later we obtain the result by combining the Eq. (9), (13), and (14)

\[ \Delta \mu = \frac{1}{\mu d} \sqrt{\frac{\exp(\mu d)}{I'}} \]  (15)

Finally, we have to calculate partial derivia to determine mathematical expression of the best measurement condition. We let the derivia equal to zero and we will get the correlation formula.

\[ f'(d) = -\frac{\exp(\mu d)}{I'} \cdot \frac{1}{\mu^2 d^2} + \frac{1}{2 \mu d} \frac{1}{\sqrt{\frac{\exp(\mu d)}{I'}}} = 0 \]  (16)

The result is: \( \mu \rho d = 1 \)

The calculation of the each situation shows that the measurement of thick one is more accurate. Its errors are under 0.5%. From Eq. (2), we can calculate that the thickness of the best situation is 5.8cm. In ideal condition, the thickness of the thick plate is closer to the thickness which calculated by Eq. (2). It is clear that errors of the thick one will be smaller. The fact reaches agreement. Adding the standard plates help to let the total thickness closer to ideal thickness. So, the result is reasonably correct in some situations.

4.2. Error analyses
After calculation, we also analyze the source of errors and reasons which cause errors.
(1) The intensity of the certain-intensity gamma ray is not a stationary value. It obeys Poisson distribution.

(2) The count rate of the ray detected by sensors has statistical error.

(3) After several-times abrasion, thickness of the standard PVC plates can not be 1 centimeters any more.

(4) We theoretically consider the radiation source as the narrow beam. Oppositely, the attenuation in different location are different for the same thickness.

There are all the possibilities of the causes of errors in our consideration which may maintain 95% possibilities.

5. CONCLUSION

In the experiment, we use the gamma ray to measure thickness of PVB plates and we summarize the following conclusions

(1) The measurement method is convenient to operate within a few basic experimental devices. It will not take plenty of energy to do the preparation.

(2) According to the analysis of the experiment, the data do not show any unusual numeral value and the calculated errors are still in a reasonable range. The experimental phenomenon validates that this measurement is reliable in some controlled situation (at least in research).

(3) In the light of errors analyses, the average standard error is below the 5.00%, which could make the method as the best thickness measurement.

(4) When the variables reach the condition that product of $\mu, \rho$, and $d$ is 1, the measurement result will be more accurate. The measurement method could be extended to multi-phase condition.

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