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Study on absorption coefficients of dual-energy γ-rays in determining phase fractions of multiphase flows

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Abstract: This paper discusses the principle and mathematical method to measure the phase fractions of multiphase flows by using a dual-energy gamma-ray system. The dual-energy gamma-ray device is composed of radioactive isotopes of ^{241}Am and ^{137}Cs with emission energies of 59.5 keV and 662 keV respectively. A rational method to calibrate the absorption coefficient was introduced in detail. The statistical error has been analyzed on the basis of the accurate absorption coefficient which enables determination phrase fractions almost independent of the flow regime. Improvement has been achieved on the measurement accuracy of phase fractions.

Key words: Absorption coefficient, γ-rays, Dual-energy, Phase fraction
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INTRODUCTION

The imaging and measurement of multiphase flows has received much attention in recent years, largely because of a need in the oil industry to measure the mass flow rates of oil, water and gas in production pipelines, and the ability to see through objects and make quantitative measurements of the enclosed materials and structures has wide range of applications. However, measurement over a wide range of flow regimes and the ability to very accurately measure the mass flow rates of each component require detailed knowledge on the hydrodynamics of multiphase flow systems, especially the phase fraction of each component on the cross-section of a pipeline, as the fast changing phase fractions directly control multiphase flow behavior and flow rates, and also the basic information to reconstruct the flow pattern images. Therefore, many researchers concentrate their attention on determining phase fractions and on improving phase fraction measurement accuracy. Radiation techniques are being considered as a better option to get the details of multiphase flow structure, since we can obtain information on the phase distribution non-intrusively. The work presented in this paper is aimed at examining how γ-rays could be used in a particular field of industrial imaging, the imaging and measurement of multi-component fluid flows or multiphase flows in pipelines. Specifically, the possible role of γ-ray techniques in an application for the oil industry that requires accurate measurement of the flow rates of oil, water and gas in oil production pipes is examined, but firstly to figure out the phase fraction by radiation techniques.

The radiation technique studied in this work involves a dual-energy γ-rays system. Water, gas, and oil in the test section attenuate radiation without the radiation depositing significant amounts of energy. The gas phase has less attenuating power for radiation, so the attenuation of gas can be neglected. So by detecting the attenuation of the radiation beams, we can measure the phase fraction in the flow channel.

Chen *et al*.(1998) measured the time-average gas holdup distributions in a pipeline by using a CT scanner. Kemoun *et al.*(2001) measured the gas holdup and its cross-sectional distribution in bubble columns using γ-ray CT. Grassler and Wirth (2001) used dual-energy X-ray tomography to characterize the vertical multiphase flows. Abro and Johansen (1999) measured the void fraction by means of multi-beam γ-ray attenuation system. Yin *et al.*(2002) measured the liquid holdup in a large scale packed column. Boyer and Fanget (2002) measured the liquid flow distribution in a large diameter trickle bed reactor. Stahl and von Rohr (2004) measured the void fraction of gas-liquid two-phase flow in pipes using single-beam gamma-densitometry.

In previous investigations, many researchers applied radiation technique on two-phase flows. However, very few studies have been reported on measurements of cross-sectional phase fractions of multiphase mixtures. This paper is aimed at applying dual-energy γ-ray radiation technique to measure the cross section phase fraction in multiphase flows.

DUAL-ENERGY THEORY

Basic principles

Attenuation of γ-rays passing through an object of thickness L is given by

$$\ln(I/I_0)=-\mu L \tag{1}$$

where μ is the mean linear attenuation coefficient of the material, I_0 represents the incident (upon the object) intensity of the γ-ray beam, I is the intensity of the γ-ray beam emerging from the object and L is the material thickness. In this paper, we will concentrate our attention on multiphase mixtures. Eq.(2) describes the relevant relations when γ-ray passes through different materials:

$$\ln(I/I_0)=-\mu_1 L_1-\mu_2 L_2-\mu_3 L_3-\cdots \tag{2}$$

where subscripts 1, 2, 3, … denote the materials with different linear attenuation coefficients.

Dual-energy model

According to Eq.(2), when a γ-ray with dual-energy source passes through an object composed of oil, water and air, the intensity attenuation is:

$$\begin{cases}\mu_{\mathrm{w}Am}L_{\mathrm{w}}+\mu_{\mathrm{o}Am}L_{\mathrm{o}}+\mu_{\mathrm{a}Am}L_{\mathrm{a}}=-\ln(I/I_0)_{Am}\\ \mu_{\mathrm{w}Cs}L_{\mathrm{w}}+\mu_{\mathrm{o}Cs}L_{\mathrm{o}}+\mu_{\mathrm{a}Cs}L_{\mathrm{a}}=-\ln(I/I_0)_{Cs}\\ L_{\mathrm{w}}+L_{\mathrm{o}}+L_{\mathrm{a}}=L\end{cases} \tag{3}$$

where subscripts Am and Cs denote the γ-rays transmitted by the source of ^{241}Am and ^{137}Cs respectively. And the subscripts ‘w’, ‘o’ and ‘a’ denote the material of water, oil and air respectively.

In this study, the attenuation of air is so small that it can be neglected, so Eq.(3) can be written as:

$$\begin{cases}\mu_{\mathrm{w}Am}L_{\mathrm{w}}+\mu_{\mathrm{o}Am}L_{\mathrm{o}}=-\ln(I/I_0)_{Am}\\ \mu_{\mathrm{w}Cs}L_{\mathrm{w}}+\mu_{\mathrm{o}Cs}L_{\mathrm{o}}=-\ln(I/I_0)_{Cs}\end{cases} \tag{4}$$

Solving Eq.(4) yields the thickness of water and oil in the test section. If the total thickness of the test section is known, we can get the thickness of the air:

$$L_{\mathrm{a}}=L-L_{\mathrm{w}}-L_{\mathrm{o}} \tag{5}$$

where L is the total thickness of the test section.

EXPERIMENT SETUP

A main advantage of dual-energy γ-ray is that it can be used to measure the water, oil and gas fraction in a pipeline simultaneously. The dual-energy γ-ray sources adopted in our study are ^{241}Am and ^{137}Cs with energies of 60 keV and 660 keV respectively. By combining the intensities measurement of narrow beams of low- and high-energy γ-rays transmitted through the test pipe, phase fractions can be determined. A transparent rectangular pipe was used in the experiment. The experimental setup is shown in Fig.1.

Fig.1 The experiment setup

CALIBRATION OF THE ATTENUATION COEFFICIENT

To determine the attenuation coefficient is very important in the measurement of phase fraction in multiphase flows by using the dual-energy γ-ray system. Generally, we can use three methods to get the attenuation coefficient.

Method one is to put one material with thickness L in the test section. From the intensity of γ-ray beams, we can get the attenuation coefficient:

$$\mu = -\ln(I/I_0)/L \tag{6}$$

Method two is to fill the test section with water and oil. The attenuation coefficient can be obtained by changing their ratio and using Eq.(2). For example, we can get the attenuation coefficient of ^{241}Am by solving:

$$\begin{cases} \mu_{\mathrm{w}Am} L_{\mathrm{w}1} + \mu_{\mathrm{o}Am} L_{\mathrm{o}1} = -\ln(I/I_0)_1 \\ \mu_{\mathrm{w}Am} L_{\mathrm{w}2} + \mu_{\mathrm{o}Am} L_{\mathrm{o}2} = -\ln(I/I_0)_2 \end{cases} \tag{7}$$

where the subscripts 1 and 2 denote the different thickness of the water or oil.

Method three is to fill the test section with the oil and water whose holdup is θ; from Eq.(2) we obtain the equations:

$$\frac{-\ln(I/I_0)_{Am}}{L} = (\mu_{\mathrm{w}Am} - \mu_{\mathrm{o}Am})\theta + \mu_{\mathrm{o}Am} \tag{8}$$

$$\frac{-\ln(I/I_0)_{Cs}}{L} = (\mu_{\mathrm{w}Cs} - \mu_{\mathrm{o}Cs})\theta + \mu_{\mathrm{o}Cs} \tag{9}$$

With different θ, we can get the different values in the left of Eqs.(8) and (9), which can be written as F_{Am} and F_{Cs}. Then by fitting them we can get the attenuation coefficient.

In this study, the attenuation coefficients were obtained by using the above methods listed in Table 1.

Table 1 The attenuation coefficients with different method

Method	$\mu_{\mathrm{w}Am}$	$\mu_{\mathrm{w}Cs}$	$\mu_{\mathrm{o}Am}$	$\mu_{\mathrm{o}Cs}$
1	0.16538	0.07396	0.13339	0.06409
2	0.16602	0.07238	0.13002	0.06083
3	0.16661	0.07454	0.13041	0.06407

Fig.2 shows test data with different attenuation coefficient. x-axis is actual water fraction and y-axis is metrical water fraction. From it we can see that better result can be obtained by using Method 3. So we will use the attenuation coefficient obtained from Method 3 in the following section.

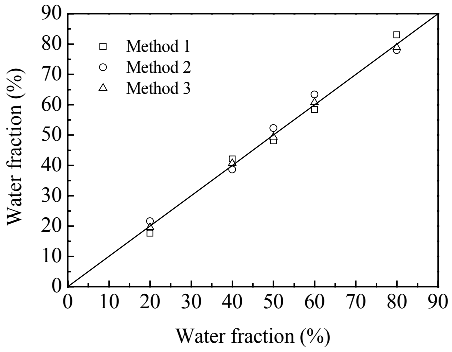

Fig.2 The test data with different attenuation coefficients

ESTIMATION STATISTICAL ERROR ON WATER AND OIL FRACTION

There are several measurement uncertainties in the experiment. Here we only discuss the statistical error due to the random character of photons emission. As a matter of fact, with the gamma source the number of emitted photons obeys the Poisson law. The statistical error for measured photons I is then expressed as

$$\mathrm{d}I/I = \pm 1/\sqrt{I} = \pm 1/\sqrt{\Phi T_{\mathrm{meas}}} \tag{10}$$

where Φ is the photons flux and T_{meas} is the measuring time.

From Eq.(4) we get:

$$L_{\mathrm{w}} = \frac{-\mu_{\mathrm{o}Cs} \ln(I/I_0)_{Am} + \mu_{\mathrm{o}Am} \ln(I/I_0)_{Cs}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs} - \mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}} \tag{11}$$

$$L_{\mathrm{o}} = \frac{-\mu_{\mathrm{w}Am} \ln(I/I_0)_{Cs} + \mu_{\mathrm{w}Cs} \ln(I/I_0)_{Am}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs} - \mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}} \tag{12}$$

So, the fractions of water and oil are

$$\theta_{\mathrm{w}} = \frac{L_{\mathrm{w}}}{L} = \frac{-\mu_{\mathrm{o}Cs} \ln(I/I_0)_{Am} + \mu_{\mathrm{o}Am} \ln(I/I_0)_{Cs}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs} - \mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}} \cdot \frac{1}{L} \tag{13}$$

$$\theta_{\mathrm{o}}=\frac{L_{\mathrm{o}}}{L}=\frac{-\mu_{\mathrm{w}Am}\ln(I/I_0)_{Cs}+\mu_{\mathrm{w}Cs}\ln(I/I_0)_{Am}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}}\cdot\frac{1}{L} \tag{14}$$

The resulting errors of water fraction θ_{w} and oil fraction θ_{o} in linear attenuation measurement become:

$$\frac{\partial\theta_{\mathrm{w}}}{\partial I_{Am}}=\frac{-\mu_{\mathrm{o}Cs}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}}\cdot\frac{1}{LI_{Am}} \tag{15}$$

$$\frac{\partial\theta_{\mathrm{w}}}{\partial I_{Cs}}=\frac{-\mu_{\mathrm{o}Am}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}}\cdot\frac{1}{LI_{Cs}} \tag{16}$$

$$\frac{\partial\theta_{\mathrm{o}}}{\partial I_{Am}}=\frac{-\mu_{\mathrm{w}Cs}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}}\cdot\frac{1}{LI_{Am}} \tag{17}$$

$$\frac{\partial\theta_{\mathrm{o}}}{\partial I_{Cs}}=\frac{-\mu_{\mathrm{w}Am}}{\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}}\cdot\frac{1}{LI_{Cs}} \tag{18}$$

According to the error propagation law, we can get the statistical errors of the fractions of water and oil as:

$$\sigma_{\theta_{\mathrm{w}}}=\sqrt{\frac{1}{\left(\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}\right)^2L^2}\left(\frac{\mu_{\mathrm{o}Cs}^2}{I_{Am}}+\frac{\mu_{\mathrm{o}Am}^2}{I_{Cs}}\right)} \tag{19}$$

$$\sigma_{\theta_{\mathrm{o}}}=\sqrt{\frac{1}{\left(\mu_{\mathrm{w}Am}\mu_{\mathrm{o}Cs}-\mu_{\mathrm{w}Cs}\mu_{\mathrm{o}Am}\right)^2L^2}\left(\frac{\mu_{\mathrm{w}Am}^2}{I_{Cs}}+\frac{\mu_{\mathrm{w}Cs}^2}{I_{Am}}\right)} \tag{20}$$

For a typical measurement case, where the test section is filled with water, oil and gas, it was assumed that each detector measures the photons flux with an error described in Eqs.(15)~(18).

The above discussion indicates that the random character of photons emission could cause some statistical errors in the phase fraction. In our work, the data acquisition time was approximately one hundred seconds in each case. Fig.3 shows the standard errors of oil and water phase fractions caused by the random character of photons emission. Based on the above analysis, we can conclude that it is possible to measure cross-section phase fraction without significant statistical error.

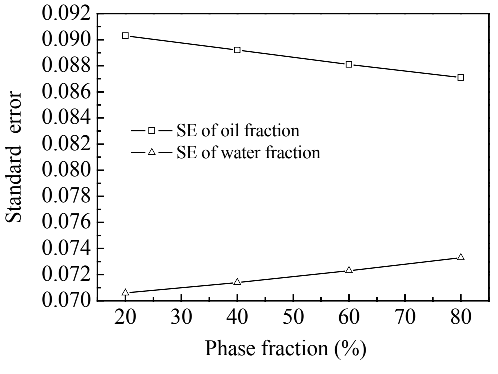

Fig.3 The standard error of oil and water fraction

CONCLUSION

This paper discusses the principle and mathematical method to measure the phase fractions of multiphase flows by using a dual-energy γ-ray system. There are three methods to get the attenuation coefficient. Analysis of experimental results showed that the attenuation coefficient obtained by fitting the data is better than others. The statistical error was analyzed on the basis of the accurate absorption coefficient. It is possible to make a cross-section phase fraction measurement without any significant statistical error which enables determination of phrase fractions almost independently of the flow regime. The results of this study showed that the dual-energy γ-ray technique can be used to measure three phase flow.

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