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Nuclear Science and Techniques, Vol.17, No.2 (2006) 86–91

NUCLEAR SCIENCE AND TECHNIQUES

Studies on absorption coefficients of dual-energy γ-rays and measuring error correction for multiphase fraction determination

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Abstract In this article**,** principle and mathematical method of determining the phase fractions of multiphase flows by using a dual-energy γ-ray system have been described. The dual-energy γ-ray device is composed of radioactive isotopes of ^{241}Am and ^{137}Cs with γ-ray energies of 59.5 and 662 keV, respectively. A rational method to calibrate the absorption coefficient was introduced in detail. The modified arithmetic is beneficial to removing the extra Compton scattering from the measured value. The result shows that the dual-energy γ-ray technique can be used in three-phase flow with average accuracy greater than 95%, which enables us to determine phase fractions almost independent of the flow regime. Improvement has been achieved on measurement accuracy of phase fractions.

Key words Absorption coefficient, Phase fraction, Dual-energy γ-rays, Multi-phase flow, Error correction

CLC number TP391

1 Introduction

The imaging and measurement of multiphase flows have received much attention in recent years, largely driven by the need in oil industry to measure the mass flow rates of oil, water and gas in the production pipelines. The ability to see through objects and make quantitative measurements of the enclosed materials and structures has a wide range of applications. However, the measurement over a wide range of flow regimes and the ability to measure mass flow rates of each component with high accuracy require the detailed knowledge of hydrodynamics of multiphase flow systems, especially the phase fraction on the cross-section of a pipeline for each component, as the fast changing phase fractions directly control the multiphase flow behavior and flow rates, and also the basic information to reconstruct the flow pattern images. Therefore, in recent years many researchers have devoted their attention to the determining of phase fractions and to improving phase fraction measurement accuracy. Radiation technique is being considered as a better option to get the details of multiphase flow structure, since we can obtain information about the phase distribution destructively. The motivation for the work presented in this article was to examine how γ-rays could be used in a particular field of industrial imaging, i.e. 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 of oil industry that requires figuring out the phase fraction by accurately measuring flow rates of oil, water and gas in the oil production pipes should be examined.

The radiation technique studied in this work is associated with a dual-energy γ-rays system. Water and oil in the test section attenuate γ-radiation without depositing significant amounts of energy. As gas phase

Supported by National Natural Science Foundation of China (No.10572143) and Joint Project between the Royal Society and the Chinese Academy of Sciences (No.15933).

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Received date: 2005-07-11

has little attenuating power for γ-radiation, the attenuation of gas can be neglected. Therefore, by detecting the attenuation of γ-radiation beam, we can measure the phase fraction in the flow channel.

Chen *et al.*[1] measured the time-average gas holdup distributions using a CT scanner. Kemoun *et al.*[2] measured the gas holdup and its cross-sectional distribution in bubble columns using γ-ray CT. Grassler *et al.*[3] used the dual-energy X-ray tomography to characterize the vertical multiphase flows. Abro *et al.*[4] measured the void fraction by means of multi-beam γ-ray attenuation system. Yin *et al.*[5] measured the liquid holdup in a large-scale packed column. Boyer *et al.*[6] have measured the liquid flow distribution in a trickle bed reactor of large diameter. Peter *et al.*[7] have measured the void fraction of gas-liquid two-phase flow in pipes using single-beam γ-densitometry.

In previous investigations, many researchers have applied the radiation technique in two-phase flows. However, very few studies have been reported on measurements of cross-sectional phase fractions of multiphase mixtures. In this article, we aim at applying the dual-energy γ-ray radiation technique to determine the cross-section phase fraction in a multiphase flow.

2 Dual-energy theory

2.1 Basic principles

The attenuation of the γ-rays through an object of thickness L is given by

$$\ln\left(\frac{I}{I_0}\right) = -\mu L \tag{1}$$

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 emerging from the object and L is the material thickness. In this article, we will focus our attention on multiphase mixtures. When γ-rays pass through different materials, they satisfy the following relation:

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

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

2.2 Dual-energy model

According to Eq. (2), when γ-rays from the dual-energy source pass through the object composite of oil, water and air, the intensity attenuation yields

$$\begin{cases} \mu_{\mathrm{wAm}} L_{\mathrm{w}} + \mu_{\mathrm{oAm}} L_{\mathrm{o}} + \mu_{\mathrm{aAm}} L_{\mathrm{a}} = -\ln\left(\dfrac{I}{I_0}\right)_{\mathrm{Am}} \\ \mu_{\mathrm{wCs}} L_{\mathrm{w}} + \mu_{\mathrm{oCs}} L_{\mathrm{o}} + \mu_{\mathrm{aCs}} L_{\mathrm{a}} = -\ln\left(\dfrac{I}{I_0}\right)_{\mathrm{Cs}} \\ L_{\mathrm{w}} + L_{\mathrm{o}} + L_{\mathrm{a}} = L \end{cases} \tag{3}$$

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

In this study, as I_0 represents the intensity of γ-ray beam after it passes through the empty pipe, the thickness of the pipe wall has no effect on the phase fraction, and the attenuation of air is so small that it can be neglected. Hence, Eq. (3) can be written as

$$\begin{cases} \mu_{\mathrm{wAm}} L_{\mathrm{w}} + \mu_{\mathrm{oAm}} L_{\mathrm{o}} = -\ln\left(\dfrac{I}{I_0}\right)_{\mathrm{Am}} \\ \mu_{\mathrm{wCs}} L_{\mathrm{w}} + \mu_{\mathrm{oCs}} L_{\mathrm{o}} = -\ln\left(\dfrac{I}{I_0}\right)_{\mathrm{Cs}} \end{cases} \tag{4}$$

By solving Eq. (4) we get the thickness of water and oil in the test section. If the total thickness of the test section is known, we can measure 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.

3 Experimental setup

3.1 γ-ray source

In this study, the dual-energy γ-ray system is composed of two radioactive isotopes of ^{241}Am and ^{137}Cs which emit γ-rays with energies of 59.5 and 662 keV, respectively. Both radioactive isotopes are assembled and shielded together in a thick lead pot to prevent the harmful high-energy emission of ^{137}Cs. The radiation activity of the isotopes is 3.7 and 0.74

GBq for ^{241}Am and ^{137}Cs, respectively. The reason for choosing ^{241}Am with much more activity than that of ^{137}Cs is that ^{241}Am γ-rays with lower energy would be weakened in penetration of the measured pipe. A collimated single γ-ray beam (diameter 20 mm) radiates from the bottom of the source pot and can be turned on/off by a mechanic switch to ensure the operation safety.

3.2 Scintillator detector

An important step in the dual-energy γ-ray system design is the selection of scintillation detectors. Two parameters are important while selecting the scintillation detectors: detection efficiency and decay constant of the scintillator. High detection efficiency is required to reduce the source strength and short decay constant contributes to a high count rate to avoid pulse pile-up or saturation. NaI (T1) crystal is most commonly used scintillator for its high detection efficiency, which is very important for ^{137}Cs because of its high-emission energy (662 keV) and strong penetrating ability.

A column crystal of scintillator with a size of 40 mm (height) × 40 mm (diameter) was coupled with a photomultiplier tube (PMT). The total diameter of the detector (ϕ) is 55 mm and the length is 220 mm. In addition, a collimation hole with a size of 50 mm × 30 mm × 150 mm (length × width × height) was mounted on the top of the detector.

3.3 Nuclear instruments

The nuclear instrument presented in this study was designed as a multi-channel instrument. The system is operated in count mode. It is composed of high voltage supply, amplifier, shaping amplifier and programmable data acquisition system (see Fig. 1).

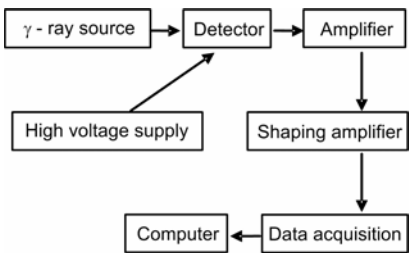

Fig. 1 Nuclear instruments.

3.4 Experimental setup

As the experiment was static, an experimental stack and four square vessels were designed as static test stack which stood apart from the multiphase flow loop and need not be cleaned, and could also serve as a static calibration stack in further work. The stack was 1 m high and supported the γ source pot on its top. The plexiglass vessel (600 mm × 100 mm × 100 mm, L × W × H) with 5-mm thick wall was designed to accommodate the oil-water-gas three-phase media. The vessel worked in horizontal direction with a total thickness of 110 mm and the valid space of 100 mm. The position of the rectangular vessel between the γ-ray source and the detector could be adjusted by two jacks depending on the experiment requirements (Fig. 2).

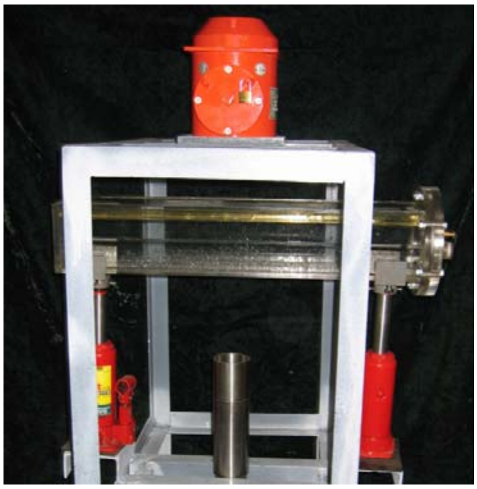

Fig. 2 Experimental setup.

4 Calibration of attenuation coefficient

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

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

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

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

$$\begin{cases} \mu_{\mathrm{wAm}} L_{\mathrm{w}1} + \mu_{\mathrm{oAm}} L_{\mathrm{o}1} = -\ln\left(\dfrac{I}{I_0}\right)_1 \\ \mu_{\mathrm{wAm}} L_{\mathrm{w}2} + \mu_{\mathrm{oAm}} L_{\mathrm{o}2} = -\ln\left(\dfrac{I}{I_0}\right)_2 \end{cases} \tag{7}$$

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

Method III is to fill the test section with oil and water. If the water holdup is θ, according to Eq. (2) we obtain the following equations:

$$\frac{-\ln\left(I/I_0\right)_{\mathrm{Am}}}{L} = \left(\mu_{\mathrm{wAm}} - \mu_{\mathrm{oAm}}\right)\theta + \mu_{\mathrm{oAm}} \tag{8}$$

$$\frac{-\ln\left(I/I_0\right)_{\mathrm{Cs}}}{L} = \left(\mu_{\mathrm{wCs}} - \mu_{\mathrm{oCs}}\right)\theta + \mu_{\mathrm{oCs}} \tag{9}$$

With different θ, we can get different values on the LHS 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 we obtained by using the aforementioned methods are listed in Table 1.

Table 1 Attenuation coefficients obtained with different methods

Method	μ_{wAm}	μ_{wCs}	μ_{oAm}	μ_{oCs}
I	0.16538	0.07396	0.13339	0.06409
II	0.16602	0.07238	0.13002	0.06083
III	0.16661	0.07454	0.13041	0.06407

The statistical errors were discussed in detail in Ref. [8].

Fig. 3 shows the test data with different attenuation coefficients. *X*-axis denotes actual water fraction and *Y*-axis denotes the measured water fraction. From the previous discussion and Fig. 3 we can see that better result can be obtained by using Method III, so we will use the attenuation coefficients obtained from Method III in the following section.

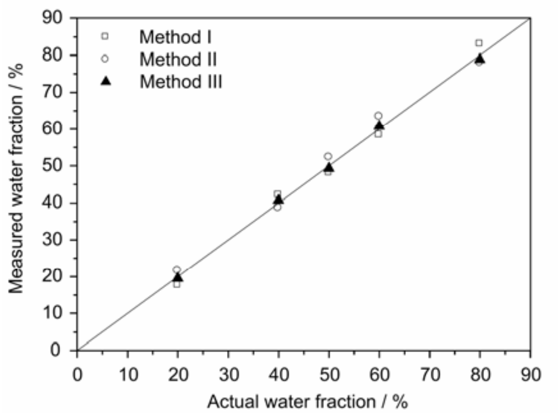

Fig.3 Test data for water fraction using different measuring methods.

5 Results and discussions

5.1 Water-air two-phase measurements

The static measurement of air-water two phase is the simplest state in multiphase flow. The test data and theoretic data of γ-ray intensity are shown in Fig. 4. From the figure we see that test data are higher than the theoretical values. A careful survey of the measured values leads us to conclude that the count rates in all cases are higher than the theoretical ones.

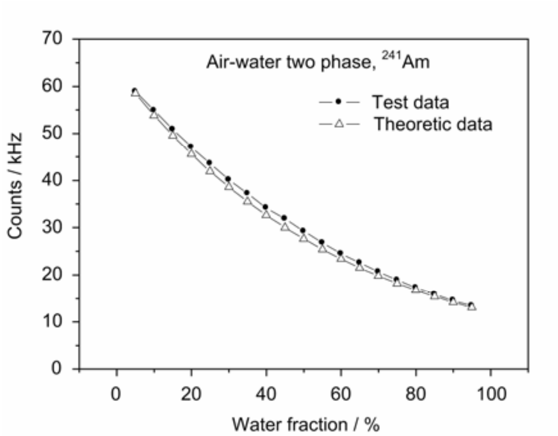

Fig.4 Gas-water two-phase attenuation.

The absolute and relative error of water fraction are shown in Fig. 5. The results show that with the increase in water fraction, the relative error decreases, but the absolute error increases. It indicates that there are extra counts being added to the measurement channel, therefore the absolute error always appears positive.

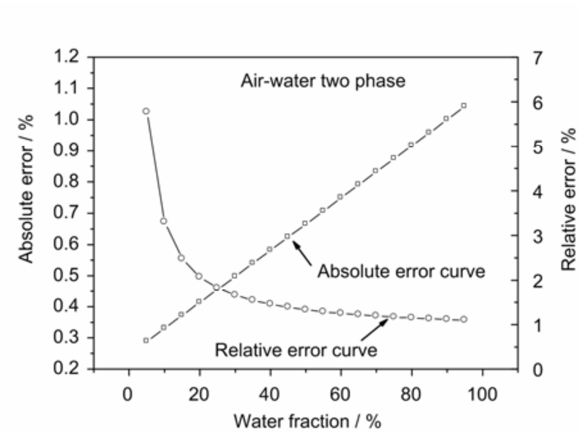

Fig.5 Absolute and relative error curves.

Compton scattering is considered to be the main explanation of this phenomenon. The γ-ray emitted by ^{137}Cs with higher energies interacts with the media, and generates the Compton scattering. As Compton scattering has a widely distributed continuous spectrum, a part of Compton scattering with lower energies will enter the ^{241}Am measurement channel, thus the extra counts are generated. In general, this error is very harmful to the measurement system, because this implies that the measurement accuracy is dependent on the flow regime. The main way to solve this problem is to make a good collimation on the scintillation detector or to modify the experimental values with the calibration error curve, i.e. to subtract the extra counts according to the error curve from the measured values. The calibration error curve shown in Fig. 6 was obtained by fitting the test data.

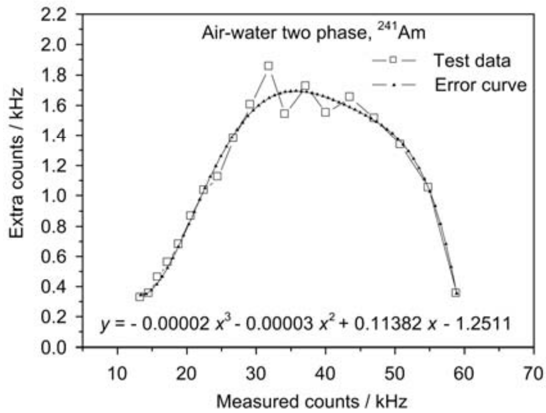

Fig.6 Calibration error curve.

5.2 Oil-water-air three phase measurements

In the three-phase fraction measurement, the dual-energy γ-ray system relies on photon attenuation in oil and water to distinguish the length of the two materials. As mentioned in Table 1, the linear attenuation coefficients of two γ-ray sources in oil and water are similar. According to Eq. (3), the similar linear attenuation coefficients may cause the small errors in the measurements of intensities to become larger, thus a modified arithmetic was developed to improve the phase fraction measurement accuracy with the aid of the calibration error curve. The results are shown in Figs. 7 and 8, respectively. It was shown that the calculated values solved directly by Eq. (3) have significant deviations. But the values calculated by the modified arithmetic have reasonable accuracy and acceptable error distribution.

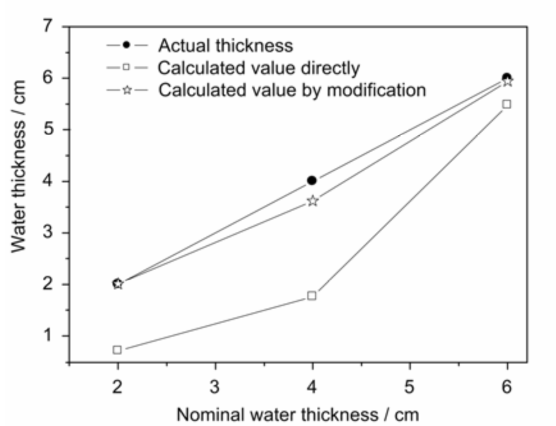

Fig. 7 Water phase fraction measurement.

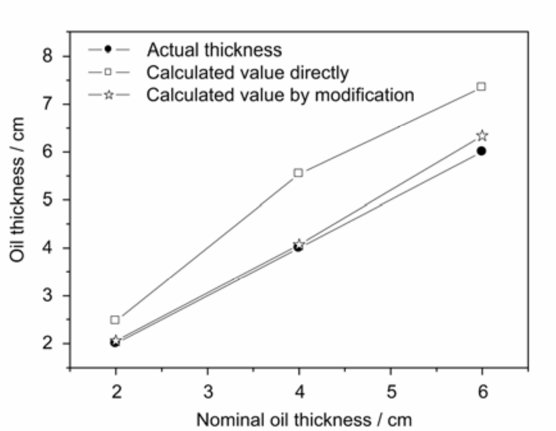

Fig.8 Oil phase fraction measurement.

From the air-water-oil three-phase measurements, it can be found that the modified results have an acceptable accuracy with a maximum error not more than 6% for every phase.

6 Conclusion

We have discussed the principle and the mathematical method to measure the phase fractions of multiphase flows by using a dual-energy γ-ray system. This technique is based on materials attenuation coefficient's measurement. There are three methods to obtain the attenuation coefficient. The analysis of experimental results shows that the attenuation coefficients obtained by fitting the experiment data are better than others. As an acceptable measurement technique, a high accuracy of γ-ray intensity is required. The modified arithmetic is conducive to removing the extra Compton scattering from the measured value. The result of this study shows that the dual-energy γ-ray technique can be used in the three-phase flow with the average accuracy greater than 95%.

Acknowledgments

The authors acknowledge Ma Naiqing, Yuan Maozhu and Ma Runhai for their collaboration and suggestions in the phase fraction determination.

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