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# Volumetric fraction measurement in oil-water-gas multiphase flow with dual energy gamma-ray system

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**Abstract:** Volumetric fraction distribution measurement is a constituent part of process tomography system in oil-water-gas multiphase flow. With the technological development of nuclear radial inspection, dual-energy γ-ray techniques make it possible to investigate the concentration of the different components on the cross-section of oil-water-gas multiphase pipe-flow. The dual-energy gamma-ray technique is based on materials attenuation coefficients measurement comprised of two radioactive isotopes of $^{241}Am$ and $^{241}Cs$ which have emission energies at 59.5 keV and 662 keV in this project. Nuclear instruments and data acquisition system were designed to measure the material's attenuation dose rate and a number of static tests were conducted at the Multiphase Laboratory, Institute of Mechanics, Chinese Academy of Sciences. Three phases of oil-water-gas media were investigated for their possible use to simulate different media volumetric fraction distributions in experimental vessels. Attenuation intensities were measured, and the arithmetic of linear attenuation coefficients and the equations of volumetric fractions were studied. Investigation of an unexpected measurement error from attenuation equations revealed that a modified arithmetic was involved and finally the system achieved acceptable accuracy in experimental research.

**Key words:** Volumetric fraction, Multiphase flow, Dual-energy γ-ray, Process tomography
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## INTRODUCTION

Oil-water-gas multiphase mixed transport in oil pipe is extensively used in ocean oil industries. How to measure the volumetric fractions of oil-water-gas multiphase flow is an important subject of study in the oil industry. Related research work was started in the 1980s. The measurement of component ratios in multiphase flows using γ-ray attenuation was first suggested by Abouelwafa and Kendall (1980), and the technique has been used in many current commercial multiphase metering systems. Single energy γ-ray technique working as a densimeter is satisfactory for two components measurement of gas/liquid or oil/water pipe-flow if we do not care about the concentration distribution of the different components in the cross-section. Dual-energy γ-ray techniques have developed rapidly in the last decade. The different attenuation properties of the three phases' media in the oil pipe are used to deduce information on the components volume fraction. Dual-energy γ-ray technique has been applied to a difficult case with three basic materials having obviously varying distribution of linear attenuation coefficients, and proved to be a very promising technique for simple and fast estimation of the volumetric fraction of oil-water-gas multiphase flow, and has become a constituent part of radial base process tomography (Grassler and Wirth, 2001).

## DUAL ENERGIES THEORIES

The following absorption law describes the mathematical connection between the γ-ray intensity $I_0$ radiated by the γ-ray source and the remaining intensity $I$ after transmission through a massive object of given length $L$ and density $\rho$ (Minder and Liechti, 1955; Morneburg, 1995):

$$I = I_0 \exp(-\eta(ZE)\rho L)$$

The absorption coefficient $\eta$ is a function of the γ-ray energy $E$ and the atom number $Z$. Under the γ-ray energy $E$, then:

$$I(E) = I_0(E)\exp(-\mu(E)L)$$

For oil-water-gas three-phase flow, the attenuation coefficient of the mixture $\mu(E)$ is represented by:

$$\mu(E) = \alpha\mu(E)_o + \beta\mu(E)_w + \gamma\mu(E)_g$$

where $\mu(E)_o$, $\mu(E)_w$ and $\mu(E)_g$ are the linear attenuation coefficients of the oil, water and gas and $\alpha$, $\beta$, $\gamma$ are the respective volumetric fractions. The transmitted intensity $I$ through a thickness $L$ of an oil/water/gas mixture is therefore:

$$I_0 \exp[-(\alpha\mu(E)_o + \beta\mu(E)_w + \gamma\mu(E)_g)L]$$

if the build-up factor is eliminated through good collimation at the source and detector. If the transmitted fluxes $I_1$ and $I_2$ at two energies $E_1$ and $E_2$ are measured, the volume fractions can be calculated if the linear attenuation coefficients of the flow components at $E_1$ and $E_2$ are known since:

$$\ln(I/I_0)_1 = -[\alpha\mu(E_1)_o + \beta\mu(E_1)_w + \gamma\mu(E_1)_g]L \quad (1)$$

$$\ln(I/I_0)_2 = -[\alpha\mu(E_2)_o + \beta\mu(E_2)_w + \gamma\mu(E_2)_g]L \quad (2)$$

$$\alpha + \beta + \gamma = 1 \quad (3)$$

There are three equations with three unknown volumetric fractions $\alpha$, $\beta$ and $\gamma$. In practice, $\mu(E_1)_g$ and $\mu(E_2)_g$ can be taken as zero without appreciable error in the volume fraction measurements because of the gas phase's low density.

The linear attenuation coefficients of water and mineral oil (kerosene) over the same energy range reveals that the differences in the photon absorption may be used to distinguish the two materials. Fig.1 shows that the photon attenuation in water is greater than that in oil. This is because oxygen has a higher atomic number than carbon, and also because water ($\rho$=1.00 g/cm$^3$) has higher density than most mineral oils (typically $\rho$=0.80~0.90 g/cm$^3$).

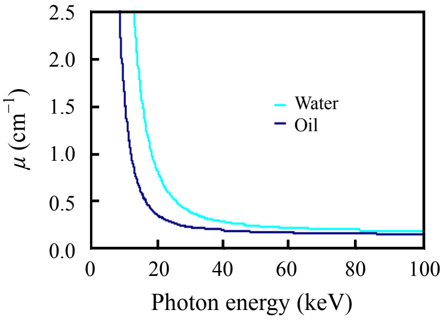


**Fig.1 Water and oil attenuation coefficients**

Since the photoelectric interaction is a stronger function of photon energy and atomic number than the Compton interaction, there is greater contrast in the linear attenuation coefficients of oil and water in the region where the photoelectric effect dominates the interaction cross-section of both materials (Key, 1999). This is illustrated in Fig.2, where the relative difference in the linear attenuation coefficients is plotted as a function of photon energy for the same energy interval. It indicates that the γ-ray measurement system relying on photon attenuation in oil and water to distinguish the two materials would yield maximum discrimination in the energy region below 40 keV.

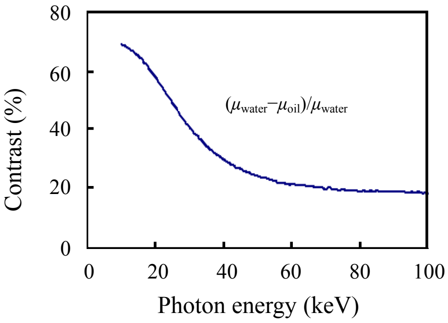


**Fig.2 Radiographic contrast between oil and water**

In this project, the γ-ray system is comprised of two radioactive isotopes of $^{241}Am$ and $^{137}Cs$ which have emission energies at 59.5 keV and 662 keV. The lower γ-ray energy is higher than 40 keV, so that the linear attenuation coefficients of two energies in oil and water are somewhat closer than expected. The necessary condition that the above equation is linearly independent must be:

$$\frac{\mu(E_1)_\mathrm{w}}{\mu(E_1)_\mathrm{o}} \neq \frac{\mu(E_2)_\mathrm{w}}{\mu(E_2)_\mathrm{o}}$$

But the too close linear attenuation coefficients of the two energies may translate small intensity measurement errors into large errors in thickness estimation; this situation is avoided only by proper selection of the energies.

## EXPERIMENTAL SETUP

### γ-ray source

In this project, the γ-ray system is comprised of two radioactive isotopes of $^{241}Am$ and with emission energies of 59.5 keV and 662 keV. Both radioactive isotopes were assembled and shielded in a thick lead pot together to prevent harmful high energy emission of $^{137}Cs$. The radiation intensity of the two isotopes was 100 mCi and 20 mCi respectively. The reason for choosing the radiation intensity of $^{241}Am$ was it has lower photon energy than $^{137}Cs$ and so, weakens after penetration into the measurement pipe. A collimated single γ-ray beam (diameter 20 mm) comes out from the bottom of the source pot and can be turned on/off by a switch mechanism which can ensure operation safety.

### Scintillator detector

An important step in dual energies γ-ray design is the selection of scintillation detectors. Two parameters are important in 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 is required for high count rate to avoid pulse pile up or saturation. NaI (Tl) crystal is the most commonly used scintillator due to its high detection efficiency; it is very important for $^{137}Cs$ due to its high emission energy (662 keV) and strong penetration ability.

A 40 mm (*H*)×40 mm (*D*) column crystal of scintillator was made and assembled with a photo multiplier tube (PMT). Fig.3 shows that the total diameter of the detector is ∅55 mm and the length is 220 mm. In addition, a collimation 30 mm (*W*)×50 mm (*L*)×150 mm (*H*) hole was installed on the top of the detector.

### Nuclear instrument

The nuclear instrument used in this project was designed as a multi-channels instrument. The system is operated in count mode. It is comprised of high voltage source, amplifier, shaping amplifier and programmable data acquisition system (Fig.4).

**Fig.3 Scintillator detector**

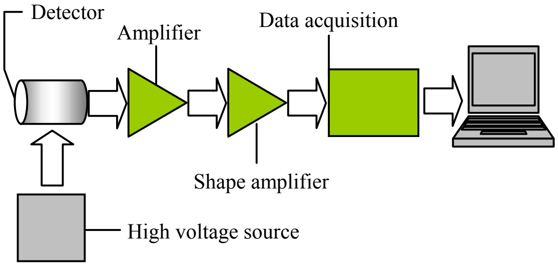


**Fig.4 Nuclear instruction**

### Experimental stack and vessel

As the experiment was static test, an experimental stack and 4 square vessels were designed as an unclear static test stack which stood apart from the multiphase flow loop, and could also serve as a static calibration stack in further work. The stack was one meter high and supported the source pot on its top. Plexiglass vessel [100 mm (*L*)×100 mm (*W*)×600 mm (*H*)] with 5 mm thick wall was designed to accommodate oil-water-gas three phase media. The vessel worked in horizontal direction and had total thickness of 110 mm and valid space of 100 mm. Its position (height) between γ-ray source and detector could be adjusted by two jacks depending on the experiment requirements (Fig.5).

## EXPERIMENTAL ARRANGEMENT

In order to survey the materials attenuation character, an experimental arrangement was designed on Table 1, total 22 measurements included in the experimental arrangement. In the valid space of 100 mm of the vessel, a minimum step of 10 mm media was changed during the experiment.

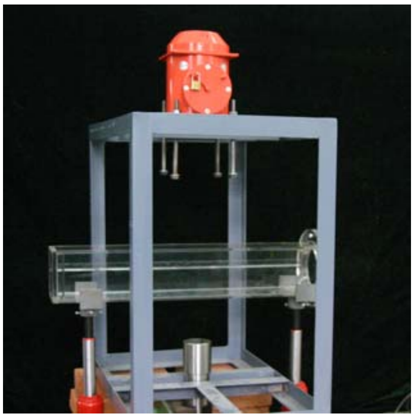


**Fig.5 Experimental stack**

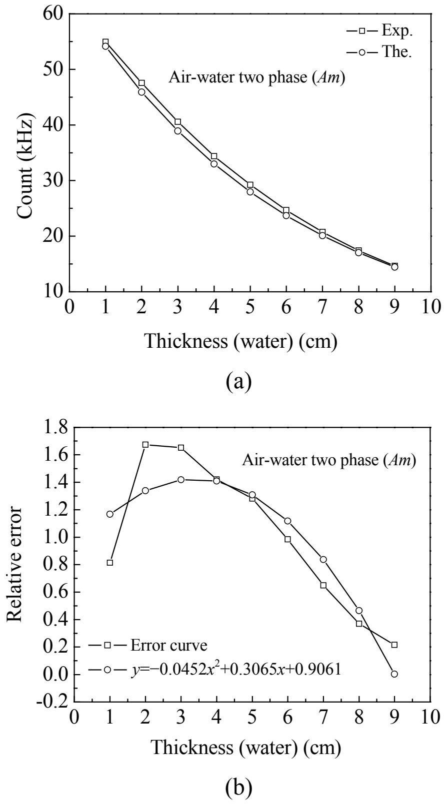
**Table 1 Experimental arrangement**

| Items | Thickness (mm) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
| 1 | | | | | | | | | | | G |
| 2 | | W | | | | | | | | G | |
| 3 | | | W | | | | | | G | | |
| 4 | | | | W | | | | G | | | |
| 5 | | | | | W | | G | | | | |
| 6 | | | | | | W, G | | | | | |
| 7 | | | | | G | | W | | | | |
| 8 | | | | G | | | | W | | | |
| 9 | | | G | | | | | | W | | |
| 10 | | G | | | | | | | | W | |
| 11 | | | | | | | | | | | W |
| 12 | | | | | | | | | | | O |
| 13 | | | G | | | | | | O | | |
| 14 | | | | | G | | O | | | | |
| 15 | | | | | O | | G | | | | |
| 16 | | | O | | | | | | G | | |
| 17 | | | W, O | | | | G | | | | |
| 18 | | | O | | W, G | | | | | | |
| 19 | | | O, G | | | | W | | | | |
| 20 | | | W | | O, G | | | | | | |
| 21 | | | G | | O, W | | | | | | |
| 22 | | | W, G | | | | O | | | | |

O=oil, W=water, G=gas

## RESULTS AND DISCUSSIONS

The static measurement of items 1~11 in Table 1 simulated the gas-water two phase flow. Although it was the simplest state in multiphase flow, the results showed that it had unexpected measurement error (Fig.6). The error curve is shown in Fig.6b. As shown in Fig.6a, measured only by $^{241}Am$, the experimental value was obviously higher than the theoretical value, especially at the medium thickness of 2~6 cm, where the errors reduce gradually to the ends of the curve. The maximum value of the error was nearly +2.6%. However, the circumstance was better in results of $^{137}Cs$; the maximum error was not more than +1.8% (Fig.7).

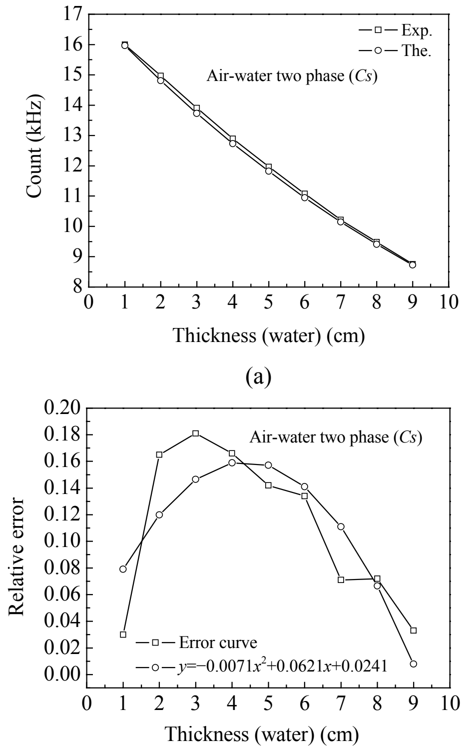


(a)

(b)

**Fig.6 Gas-water two phase attenuation measured by $^{241}Am$ (a) and its error curve (b)**

Careful study of the measurement values, showing that the count rates of all the experiment points were higher than theoretical rates, indicated that there were extra counts added to the measurement channel so that positive error always occurred in the experiment value. Compton scatter is considered to be



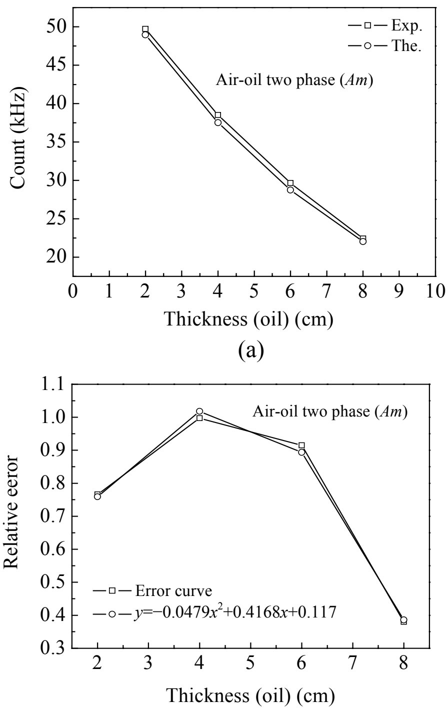
(a)

(b)

**Fig.7 Gas-water two phases attenuation measured by $^{137}Cs$ (a) and its error curve (b)**

the main explanation of this phenomenon: the higher energies γ-ray emitted by $^{137}Cs$ interact with the media cross-section to generate the Compton scatter. As Compton scatter has a widely distributed continuous spectrum, a part of the lower energies emission of Compton scatter enters the $^{241}Am$ measurement channel thus accounting for the occurrence of extra count. In general, this error is very harmful for the measurement system that means the measurement accuracy is flow regime dependent. It seems that the influence of scatter is less in the $^{137}Cs$ measurement channel; this is because the Compton scatter always emits lower energies to all the directions of space but rarely enters the $^{137}Cs$ itself in the measurement channel. The main way to solve this problem is well collimated on scintillation detector or modifies the experiment values with the calibration error curve; subtracts the extra count according to the error curve from the measurement values.

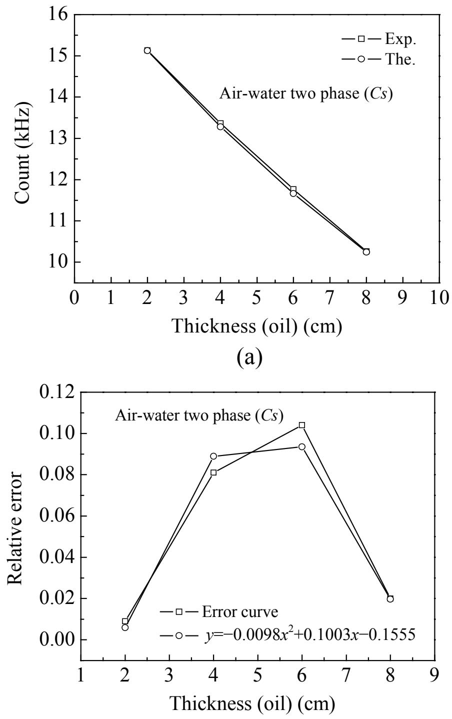
The static measurement of items 12~16 in Table 1 simulated the gas-oil two phase flow, the results and conclusions are the same for gas-water two phase flow (Figs.8 and 9).



(a)

(b)

**Fig.8 Gas-oil two phases attenuation measured by $^{241}Am$ (a) and its error curve (b)**



(a)

(b)

**Fig.9 Gas-oil two phases attenuation measured by $^{137}Cs$ (a) and its error curve (b)**

The static measurement of items 17~22 in Table 1 simulated the oil-water-gas three phase flow. In the three phase volumetric fraction measurement, as mentioned in Section 2 of this paper, the γ-ray measurement system relying on photon attenuation in oil and water to distinguish the two materials yielded maximum discrimination in the energy region below 40 keV, but the lower energy isotopes of $^{241}Am$ used in this project has emission energies at 59.5 keV, therefore the linear attenuation coefficients of the energy in oil and in water is closer than expected.

The too close linear attenuation coefficients may magnify small errors in intensities measurements into large errors by Eqs.(1), (2) and (3), thus a modification arithmetic was developed to improve the three phase measurement accuracy with the calibration error curve. The results are shown in Fig.10.

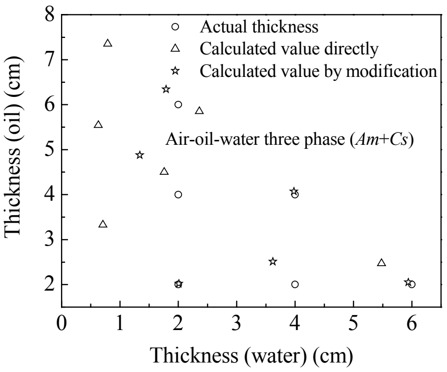


**Fig.10 Oil-water-gas three phase volumetric fraction measurement**

As shown in Fig.10, corresponding to the six given points, the six calculated values obtained directly from Eqs.(1), (2) and (3) have significant bias, the error distribution is seriously flawed. Another group of six points calculated by modification arithmetic have reasonable accuracy and acceptable error. The histogram of the results of measurement is shown in Fig.11.

The histogram of oil-water-gas three phase measurements revealed that the modified results have acceptable accuracy maximum error of not more than 6% (full scale) for every phase.

All the above results and discussions were based on static experiments, the oil-water-gas three phase media distributed in three clear layers in the vessel, but the oil-water-gas three phase medium in actual three phase pipe flow should be mixed in different distributions. But are the results of dynamic tests the same as those of static tests? Perhaps further dynamic studies should be done to answer the questions, but as we estimate the two results are close because the dual-energy gamma-ray technique is based on materials attenuation coefficients measurement, the material's attenuation dose rate is not influenced by the medium distribution in same radioactive area.

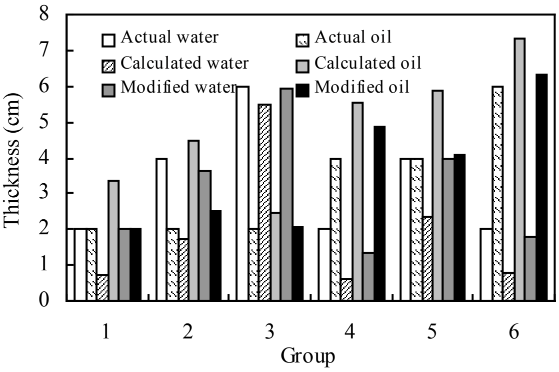


**Fig.11 Histogram of oil-water-gas three phase measurement**

## CONCLUSION

Dual-energy γ-ray techniques are based on materials attenuation coefficients measurement. In oil-water-gas three phase system, if the lower γ-ray energy above 40 keV (59 keV $^{241}Am$ in this project), the linear attenuation coefficients of the energy in oil and in water are somewhat close to each other; small errors in the intensities measurements maybe amplified into large errors in the thickness estimation obtained by Eqs.(1), (2) and (3).

As an acceptable measurement technique, it is required that the system has high accuracy of materials attenuation coefficients. The modification arithmetic is helpful for removing the extraneous Compton scatter from the measurement values.

Finally, a well designed dual-energy γ-ray system has the potential to yield accuracy better than 95% in average in oil-water-gas three phase system.

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