Estimation of the sensitivity in dual wave X-ray absorptiometry

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Abstract. Dual wave X-ray absorptiometry is considered theoretically and the application of suggested technique extends to the multiphase flow analysis. Proposed method allows for specifying dynamically the percentage of fluid components with the resolution as high as 0.25% (according to the mathematical simulating). The accuracy of this measurement is one order higher by magnitude than that provided by the state of the art flow analyzing devices.

A non-separative real time measurement is one of the most relevant technical issues discussed during a few last decades. The determination of the amount and parameters of extracted well production without usage movable details and manual process control is a very high challenge and still needs to be addressed. There is a wide variety of different approaches to measure multiphase fluid parameters. The transmission radiometric methods based on the analysis of radiation such as X-ray, gamma or neutron passed through the studied object, are the most perspective ones which are currently known [1]. Particularly, X-ray absorptiometry, which is widely used, for example in medicine and biology, is very promising [2, 3].

The state of the art for non-separative flow metering is Vx technology in which ^{133}Ba radioactive source with an activity equals to 10 mCi is used. Radiation of two different energies (in the discussed case 32 and 81 keV) is absorbed, during the passing through the multiphase medium, in varying degrees in according to the composition of medium. Analysis of the absorption degree allows determining the component composition of the three-phase medium [4]. However, radioactive isotope based devices have a few limitations which can be crucial for multiphase flow analysis. The most significant of them are relative low intensity of produced radiation, which limits minimal time of a measurement and leads to increase statistical error, and environmental hazards. In order to avoid these disadvantages, X-ray based radiation sources, which are able to provide much higher radiation flux, can be used, that promises good prospectives in application of aforementioned devices [1]. On the other hand, continuous spectrum of X-ray tubes causes essential difficulties on the stage of radiation detection and data processing. Thus, the main challenge in this area is to produce linear X-ray spectrum using continuous one.

Research and development in that direction resulted in the device implementation «X-ray based densitometer for multiphase flow measurement» [5] which is one of the most advanced devices up today realizing the radiation-based method of measurement. In this device it is suggested to generate X-ray beam having a linear spectrum of the secondary fluorescence (see for example, FluorX described in Ref. [6, 7]).

As it previously shown [1], there are a few drawbacks of proposed technology. Such, intensity of characteristic lines is significantly decreased due to the reradiation resulting in about 3 order of intensity loss compared to the primary fluorescence [8]. Also, the presence of intensive background radiation, which is comparable with the intensity of useful K_α line, increases errors. Therefore although the proposed technology helps to improve the radiation safety it does not provide a significant increase of the accuracy and rate of measurement compared to the technology based on Vx.

An alternative method based on considering a wave dispersive analysis of the radiation [9] passed through a multiphase medium was suggested by the authors of the present work. The basic idea of the method consists of the following: generation of radiation based on X-ray tube as a source of radiation, passing of complex in spectral composition radiation through the multiphase flow, extraction two narrow monochromatic lines of radiation (first and second order of diffraction), detection of these lines and analysis of their degree of absorption.

The realization of the described approach is implemented in the device described in the patent [10]. Lines of X-ray radiation with such energies as 20 and 40 keV are considered as preferable for the analysis procedure. Suggested method provides a number of advantages. Firstly, the elimination of the stage of reradiation (generation of secondary fluorescence) results in the increasing the X-ray radiation intensity what improves the accuracy and the rate of analysis. The loss of intensity due to the monochromatization in this case is determined by the reflection coefficient of radiation in the diffraction directions. This coefficient constitutes the value more than 50% that gives the loss of intensity less than the half from the initial level and yet this is still much lower than in commercially available sources, for example, Fluor'X. Besides, the proposed method ensures a much lower level of the background radiation.

To check the possibilities of the suggested method a simulation of the radiation spectrum on the different stages was performed. The tube with the argentum anode working at the cathode-anode voltage 60 kV was considered as the radiation source. Simulating was completed using the software GEANT4. In figure 1 the radiation spectra generated by the tube before and after the passing through the studied object are presented. Characteristic X-ray lines of Ag with the energy 22.1 keV was chosen as the first working line for further evaluations and the line with double energy was chosen as the second one.

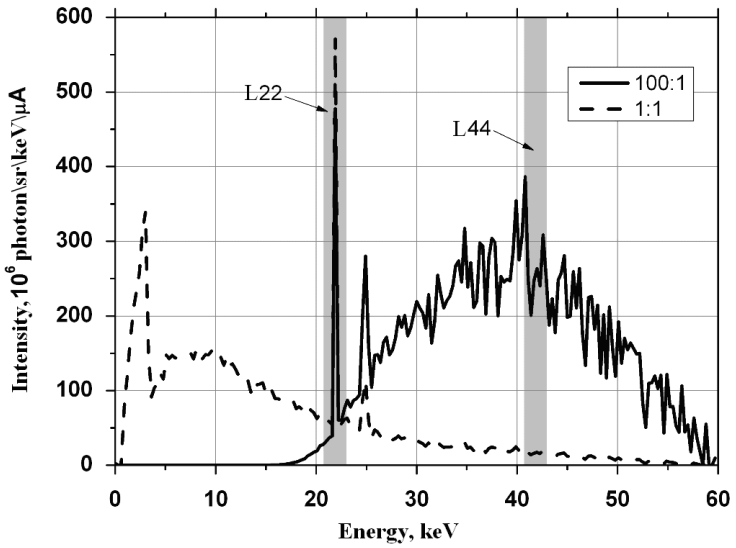


Figure 1. X-ray spectrum generated by the X-ray tube with Ag anode; the dashed line denotes the radiation before the studied object and the solid line (the magnification is by 100 times) – the radiation after the studied object.

In figure 2 X-ray spectrum passed without interaction through 73 mm of water (dashed line) and oil (solid line) after reflection from the crystal are presented. Shown spectrum are perfectly illustrating the difference in the degree of radiation absorption by different components of multiphase flow.

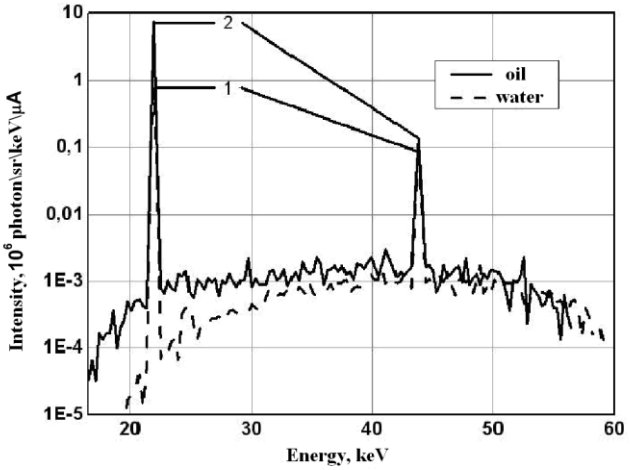
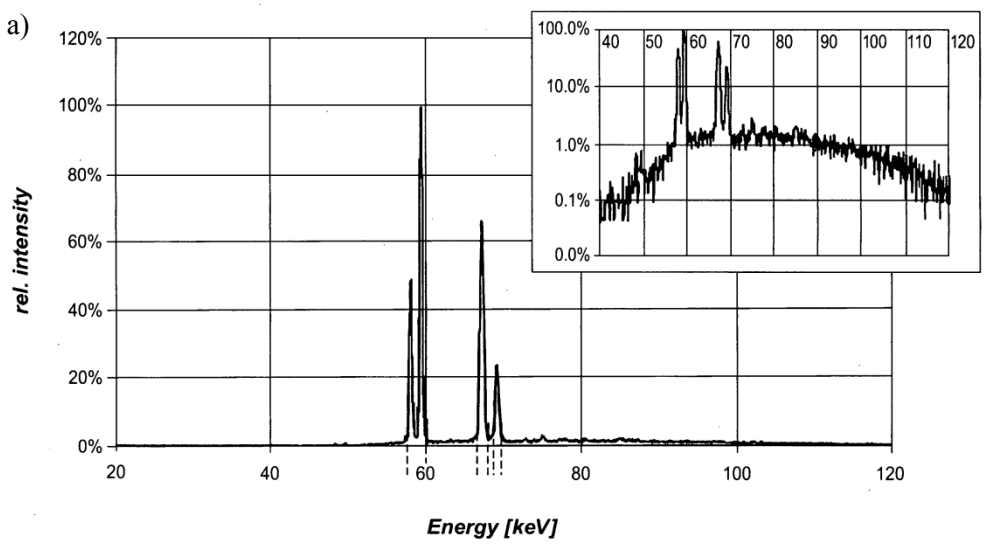


Figure 2. X-ray radiation spectrum passed without interaction through 73 mm of water (the dashed line) and oil (the solid line) after reflection from the crystal. By numbers 1 and 2 the maximal levels for water and oil are denoted, correspondingly.

As it shown in [1] and also figure 3 the ratio of number of monochromatic lines photons to the number of background radiation photons for FluorX source is close to unit, meantime by using the diffraction method to extract the analytical lines this ratio has constituted the value as low as 0.03 that points to the advantage of the discussed approach of monochromatization. Figure 3 shown here in order to provide convenience for the readers.



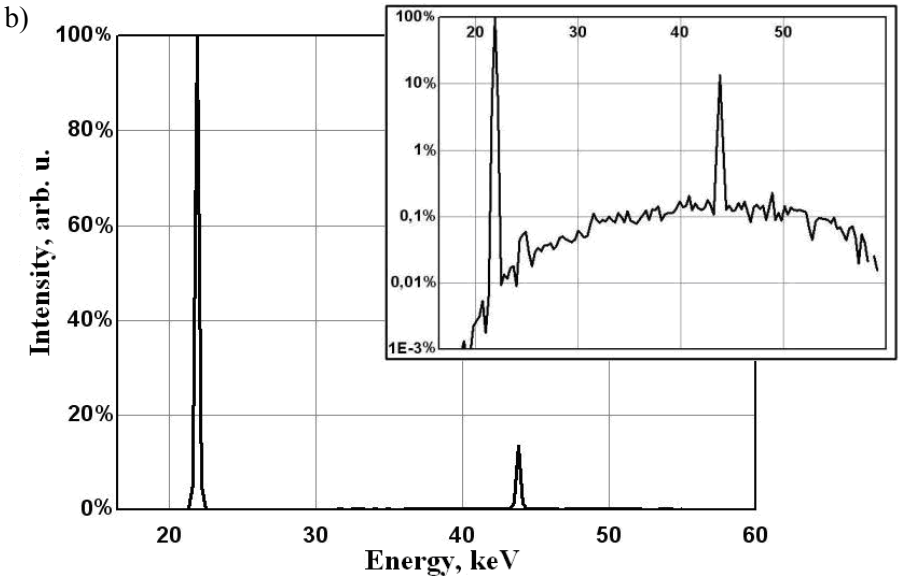


Figure 3. Radiation spectrum from X-ray radiation source are shown: a) – Fluor'X [7], b) – the proposed source.

From the other side in order to receive the statistical uncertainty on the level of stability of modern X-ray sources, it is about 0.1 % photons per second, we estimate the required time for accumulation the statistics. Under the assumption that the process of X-ray photons interaction with detector material obeys to Poisson distribution the expression for time determination reads

$$t = \frac{1}{\bar{N}\delta^2},$$

where δ is a relative statistical uncertainty, $\bar{N}$ is the average number of photons incident on the detector per second.

Thereby the required time for one measurement is $\max\{t_l, t_h\}$ in the case of source FluorX. Here l, h are indices corresponding to the line at high and low quantum energy.

$$t_l = \frac{1}{(0.0035 \cdot 10^6 \cdot 10^{-6})} = 286 \text{ sec},$$

$$t_h = \frac{1}{(0.0025 \cdot 10^6 \cdot 10^{-6})} = 400 \text{ sec}.$$

The time required for a measurement with the claimed statistical uncertainty in proposed method:

$$t_l = \frac{1}{(0.75 \cdot 10^6 \cdot 10^{-6})} = 1 \text{ sec},$$

$$t_h = \frac{1}{(0.1 \cdot 10^6 \cdot 10^{-6})} = 10 \text{ sec}.$$

In fact the device principle is based on measurement the average density (or thickness). Thereby in the first approximation the limit of accuracy should be a function of minimal its deviation which can be detected. The possibility to distinguish the specific characteristics is defined by SNR parameter describing the signal to noise ratio. The minimal value of this parameter at which the difference in the signal still can be extracted, is equal to 1. In the case of monochromatic radiation the signal to noise ratio reads

$$SNR = \frac{N_2 - N_1}{\sqrt{N_1}},$$

where N_1 is a number of photons, passed through the homogeneous medium of the thickness H (e.g. 100% water) and N_2 is a number of photons, passed through the same medium containing oil and gas. Now we evaluate the minimal linear size δ of the inhomogeneity with the absorption coefficient μ_2. The inhomogeneity is located in a homogeneous medium with the absorption coefficient μ_1. Let N_0 be a number of photons incident on the medium, N_1 and N_2 are the numbers of photons passed through the homogeneous medium with the absorption coefficient μ_1 and μ_2, correspondingly:

$$N_1 = N_0 \exp(-\mu_1 H);\ N_2 = N_0 \exp(-\mu_1 (H-\delta) - \mu_1 \delta).$$

Substituting these expressions into the equation for SNR results in

$$SNR = \frac{N_0 \exp(-\mu_1 (H-\delta) - \mu_2 \delta) - N_0 \exp(-\mu_1 H)}{\sqrt{N_0} \exp(-\frac{\mu_1 H}{2})} =$$

$$= \sqrt{N_0} [\exp(-\mu_1 (0.5H - \delta) - \mu_2 \delta) - \exp(-0.5\mu_1 H)].$$

Equating SNR to 1 we obtain the following expression

$$\exp((\mu_1 - \mu_2)\delta) - 1 = \frac{\exp(0.5\mu_1 H)}{\sqrt{N_0}}.$$

Expressing the exponent in the left part of the last equation gives:

$$(\mu_1 - \mu_2)\delta = \ln\left(\frac{\exp(0.5\mu_1 H)}{\sqrt{N_0}} + 1\right).$$

Finally

$$\delta = \frac{1}{\mu_1 - \mu_2} \ln\left(\frac{\exp(0.5\mu_1 H)}{\sqrt{N_0}} + 1\right) \approx \frac{\exp(0.5\mu_1 H)}{(\mu_1 - \mu_2)\sqrt{N_0}} = \frac{1}{(\mu_1 - \mu_2)\sqrt{N_1}}.$$

Absorption coefficients at radiation energy 44 keV for water and oil are μ_1 = 0.248 cm^{-1}, μ_2 = 0.197 cm^{-1}. These coefficients determine the minimal linear size of the oil drop which is detectable in water. Results of simulation give the number of photons passing into the solid angle 10^{-4} sr per 10 sec about N_1 = 950000. Thus for oil

$$\delta_{oil} = 0.02 \text{ cm}$$

and similarly for a methane bubble with μ_2 = 0.000234 cm^{-1} at the same energy

$$\delta_{met} = 0.0041 \text{ cm}.$$

Absorption coefficients for water, oil and methane are μ_1 = 0.655937 cm^{-1}, μ_2 = 0.337753 cm^{-1} μ_2 = 0.000374 cm^{-1} at radiation energy 22 keV that gives the number of photons N_1 = 7500000. Corresponding sizes are

$$\delta_{oil} = 0.0011 \text{ cm}$$

for oil drop in water and

$$\delta_{met} \approx 0.0007 \text{ cm}$$

for methane bubble.

Finally the minimal dimensions for methane bubble in water which are detectable equal to 41 μm and 200 μm for oil at detector loading level 10^6 counts per sec and the tube diameter by 73 mm.

Taking into account the average density 0.9 g/cm^3 for oil and 0.001 g/cm^3 for methane and expressing the minimal sizes by mass fraction one can receive

$$m_{\text{oil}} = \frac{x}{H\langle\rho\rangle}\rho_{\text{oil}} = 0.0025 = 0,25\% \text{ for oil,}$$

$$m_{\text{met}} = \frac{x}{H\langle\rho\rangle}\rho_{\text{met}} = 5.6\cdot10^{-7} = 5.6\cdot10^{-5}\% \text{ for methane bubble.}$$

Interesting to note that the threshold of the present-to-day commercially available devices is as low as 2.5% by the liquid phase and 5% by the gas phase which at least one order lower than our technology provides.

Conclusion

An approach to perform the compositional analysis of multiphase flow based on dual wave X-ray absortiometry is suggested and shown to provide the higher sensitivity in comparison with present analogues. Numerical simulations are performed and the spectrum of X-ray radiation on different stages of analysis is determined that allows for sensitivity evaluation of suggested approach. According to these evaluations a drop of oil with the linear size of 0.011 mm in a layer of water with the thickness 73 mm can be detected. Corresponding size of a gas bubble in a water layers is 0.007 mm.

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References

[1] Gogolev A, Cherepennikov Yu, Rezaev R *et al* 2015 *Adv. Mater. Res.* **1084** 252
[2] Stuchebrov S, Verigin D, Lukyanenko Y *et al* 2014 *Adv. Mater. Res.* **880** 168
[3] Stuchebrov S, Batranin A, Verigin D *et al* 2014 *Adv. Mater. Res.* **880** 53
[4] Scheers A M, Slijkerman W F J 1996 *SPE publication* 36593
[5] Patent US № 20120087467, 12.04.2012
[6] Patent US № 4903287, 20.02.1990
[7] Patent US № 5157704, 20.10.1992
[8] Griaznov A Y 2004 Development of hardware and methodical ways to improve analytical parameters of energy dispersive XRF analyzer, Dissertation of Candidate of Technical Science (PhD), St. Petersburg, (in Russian)
[9] Cherepennikov Yu, Gogolev A 2014 *Journal of Physics: Conference Series* **517** 012037
[10] Patent RU № 2559119, 10.08.2015 (in Russian)