On X-ray Source for Dual Wave Absorptiometry

Aleksey Gogolev
Tomsk Polytechnic University
Tomsk, Russia
gogolev@tpu.ru

Nikolay Filatov
Tomsk Polytechnic University
Tomsk, Russia
filatovna@tpu.ru

Mikhail Shevelev
Tomsk Polytechnic University
Tomsk, Russia
mvshev@tpu.ru

Sergey Chistyakov
Tomsk Polytechnic University
Tomsk, Russia
csg@tpu.ru

Sergey Uglov
Tomsk Polytechnic University
Tomsk, Russia
uglov@tpu.ru

Artem Vukolov
Tomsk Polytechnic University
Tomsk, Russia
vukolov@tpu.ru

***Abstract*—A new method for the formation of a dual X-ray source spectrum for the method of analyzing multiphase fluid flow based on wave dispersive X-ray absorptiometry using crystalline monochromators is proposed. The experimental results of testing the proposed method of forming the optimal X-ray spectrum are presented. A comparison with the results of numerical simulation is given.**

Keywords—X-Ray source, Vx technology, oil, multiphase fluid, flow

I. Introduction

The Vx method is the advanced level technology for accurate measurement of oil, gas and water without the phase separation. The Vx method is based on spectral analysis of the probing radiation from a radiation source ^{133}Ba. Radiation contained two different monochromatic spectral lines (in the considered case the energies are 32 and 81 keV) is absorbed passing through a medium to a different degree. The absorption depends on the composition of the medium. Analysis of the degree of absorption allows to determine component composition of three-phase medium [1]. However, the equipment based on radioactive isotopes has several limitations. These restrictions are critical for the analysis of multiphase flow. The low-intensity radiation produced by a radioactive isotope is one of the main restrictions which limits the minimum measurement time and is caused the increase of statistical error. To avoid these drawbacks one can use the X-ray tube as a radiation sources. The X-ray tube can provide a much higher radiation flux, which promises good prospects for the use in the above-mentioned devices [2].

The radiation source based on the X-ray tube was carried out in "X-ray densitometer for measurement of multiphase flow" [3] In this device, the line spectrum of secondary fluorescence was produced by the X-ray tube (see FlourX described in [4]). The proposed technology helps to improve radiation safety, however, it has several drawbacks. For example, the intensity of characteristics spectral lines is significantly reduced due to reradiating. It leads to an intensity loss about 3 orders of magnitude compared to the primary fluorescence [5]. Furthermore, the intense background radiation, which is comparable to the intensity of the useful Kα secondary fluorescence line, increases the error. Therefore, the considered technology does not significantly improve the accuracy and speed of measurement compared to Vx technology.

A similar to Vx method using the radiation generated by the X-ray tube was discussed in [6, 7]. The approach was based on the analysis of the degree of absorption of radiation from two narrow monochromatic radiation lines determined from the spectrum of the X-ray tube by the method of radiation diffraction on a crystal. Using method of generating radiation allows to obtain the ratio of the intensities of these spectral lines is about 10:1 [7]. The main disadvantage of this method is that the accuracy and measurement time are determined by a line of lesser intensity, and the intensity of the other line is excessive at the same time. It leads to an undue overload of the detector. Thus, the generation of two monochromatic spectral lines of similar immensity is desirable. Obtainment of the equal intensities of the two spectral lines can be achieved using an additional absorber, which leads to the loss of the useful intensity of the primary radiation from the X-ray tube.

In this article, we propose a new approach for the method of generating a two-component X-ray spectrum using a crystal monochromator. It allows equalizing the intensity of the X-ray spectral lines. We show the results of experimental investigation and the numerical calculation as a confirmation of the proposed approach.

II. Background

We suggest refusing the scheme with a silver anode [6, 7]. The main idea of the proposed approach is the use of scheme when the second spectral line with high energy is produced by the crystal using the characteristic X-rays of the anode material of the X-ray tube (for example, K-line of tungsten) and the first spectral line with low energy is formed by the same crystal using the continuous spectrum of bremsstrahlung.

Let us consider the proposed approach of generating X-rays with two narrow monochromatic spectral lines based on the X-ray tube with a tungsten anode (see Fig. 1).

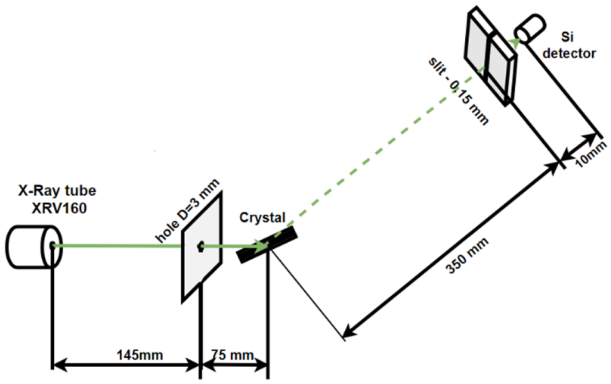

Fig. 1 The experimental scheme

The crystal analyzer is oriented in such way that the second diffraction order of the crystal coincides with the characteristic X-ray of the tungsten K-line (59.4 keV) forming the second spectral line (high energy). The radiation in the first spectral line (low energy) with the central energy of 29.7 keV

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is generated by the first diffraction order from the low energy of the continuous spectrum of bremsstrahlung radiation from the X-ray tube.

Note that the typical ratio of the spectral density radiation between the spectrum part of bremsstrahlung radiation and the radiation at the intensity peak of characteristic X-ray for the tungsten X-ray tube per 1 eV is approximately 1:10. It depends on the acceleration voltage and the tube design. It is expected that the equalization of the intensity between the first and the second peak will occur due to differences in the reflection coefficient for the first and second diffraction orders. To select a crystal the reflection coefficient can be estimated from the width of Darwin`s table as the first approximation. Estimating the widths of Darwin`s table for Ge and Si crystals (see Fig. 2 [8]) the much high intensity can be achieved using Ge crystals since the width of Darwin`s table for Ge (440) is 2.28 times larger than for Si (440).

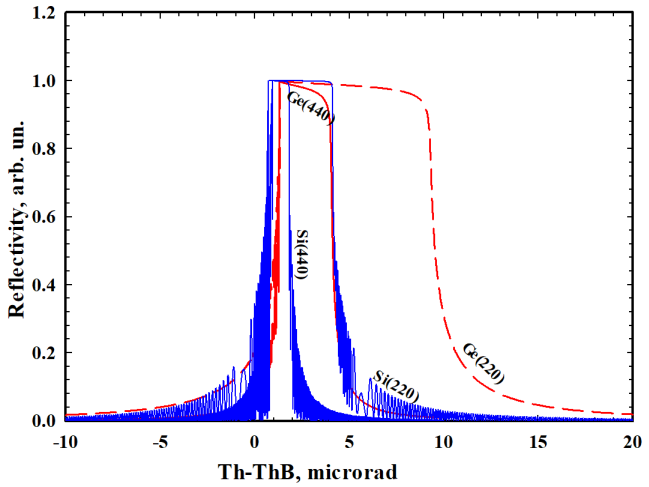

Fig.2. Darwin`s tables for the second allowed diffraction order of Si (400) and Ge (440) crystals for radiation with an energy of 59.4 keV

In real condition, the important factors besides the parameters of Darwin`s table are the angular divergence of X-rays, the focal spot size of the X-ray tube and the mosaicity of crystal, etc. Note that these factors influence the formation of the radiation intensity in the diffraction orders.

To verify the assumptions considered above, we carried out a series of experimental tests using silicon, germanium and the highly oriented paralytic graphite (HOPG) crystals. In the experiment, we use the graphite to compare the crystals with high and low mosaicity.

III. SETUP AND EXPERIMENTAL RESULTS

The experimental scheme is shown in Fig. 1. The X-ray tube with tungsten anode was used as a source of radiation. The focal spot size is Ø = 1 mm, voltage is 80 kV, the thickness of the beryllium outlet window of the X-ray tube is t = 100 um. We employ Si (220), Si (400), Ge (220) and HOPG (0002) crystals in the experiment and the thicknesses of all crystals are equal to 0.6 mm. The surface of the used crystals coincided with the indicated crystallographic planes.

Angular distribution of radiation is formed by a circle diaphragm. The diaphragm is made of lead and has 3 mm diameter, the distance between the X-ray tube to the diaphragm is 145 mm. The distance from the crystal to the X-ray tube is 220 mm. The X-rays are detected by the Si detector placed at a distance equalled 360 mm from crystal analyzer. The thickness and diameter of the Si detector are t_D = 5 mm and Ø = 13 mm, respectively. The spectrum of calibration source ^{241}Am measured by the Si detector is presented in Fig. 3. The slit with a width equal to 1.5 mm is set in front of the detector in the plane, which is perpendicular to the diffraction plane. The locations of the detector and crystal relative to the X-ray beam correspond to the Bragg angle for the crystal.

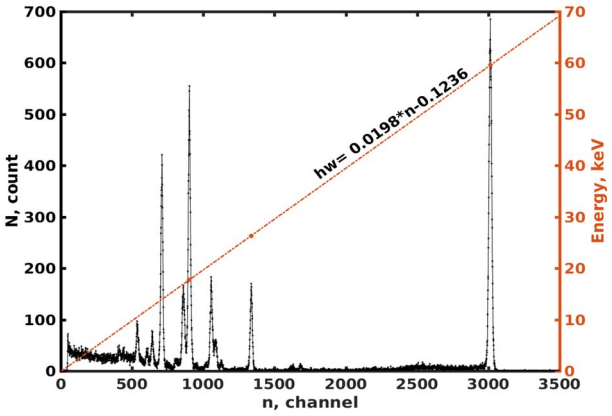

Fig.3. Spectrum of calibration source (Am241) measured by the cryogenic Si detector

We choose the Bragg angle so that energy for the second allowed diffraction order coincides with the energy of $E_{K\alpha 1}$ = 59.4 keV. We also take the Bragg angle for the pyrolytic graphite crystal HOPG (0002) so that the energy of the third (0006) diffraction order coincides with $E_{K\alpha 1}$.

Fig. 4 shows spectra and the related intensities (see Fig.5) measured for Si (220), Si (400), Ge (220) and HOPG (0002) crystals. Measurements are performed using a 0.33 mm thick copper foil as an absorber instead of the analyzed liquid. Experimental results for HOPG crystal are shown for comparison.

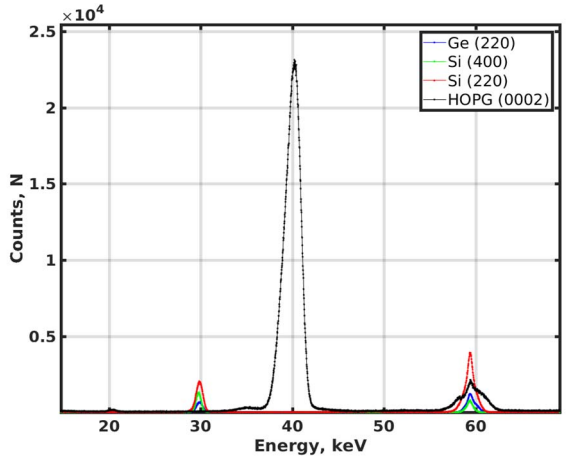

Fig.4. Measured spectra from Si (220), Si (400), Ge (220) and HOPG (0002) crystals

Despite the attractive high intensity of radiation generated for HOPG crystal, its use for Vx technology is difficult due to the small energy gap between the spectrum peaks. The energy gap certainly can be increased by decreasing the Bragg angle. However, for these conditions, one should expect a strong illumination of the detector with a direct beam. As is shown from the obtained results (see Fig. 5) for Si and Ge crystals,

the best ratio between intensities for the first and second diffraction orders is observed for Si (220) crystal.

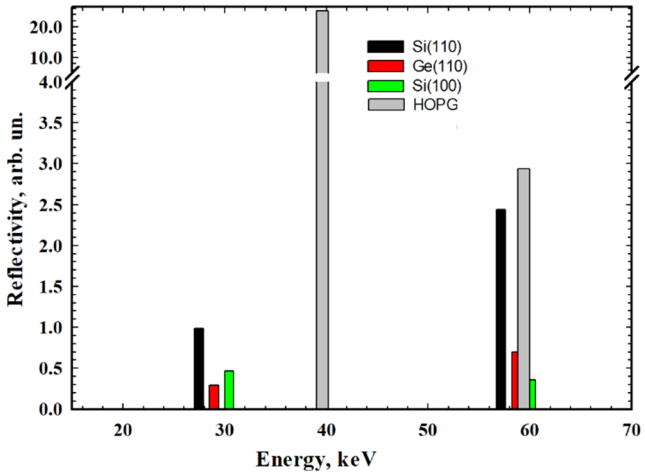

Fig. 5 Intensity of radiation measured for different diffraction orders for Si (220), Si (400), Ge (220) and HOPG (0002)

IV. SIMULATION

Numerical simulation of the process of the radiation scattering on selected crystals are performed using the special software SHADOWVUI [8].

To take into account the contribution of bremsstrahlung and the characteristic radiation of the tube with W anode we simulated its spectra by GEANT4. The results of calculation are shown in Fig.6 for several voltage bias U of the X-ray tube.

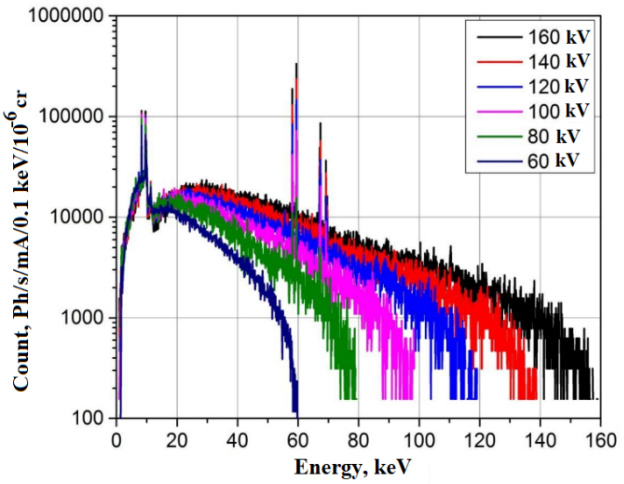

Fig. 6 The calculation of the spectra X-ray tube with W anode for several voltage bias

The relative contribution of bremsstrahlung for U = 80 keV as one can see in Fig.6 was take into account with the following weight coefficients for the spectral density: P_E = 1:1:0.5 for the quanta energies of 29.7, 39.8, 59.4 keV, respectively [8-9]. We calculate the spectral $K_{\alpha 1}$ (E = 59.4 eV) and $K_{\alpha 2}$ (E = 57.98 eV) lines using the values of the energy line width are equal to dE = 43.2 eV and dE = 37.4 eV [10], respectively. The weight coefficient is P_E = 10. Contribution of the spectral $K_{\alpha 2}$ line is simulated for the Bragg angle optimal for the spectral $K_{\alpha 1}$ line.

The simulation is performed for 10^6 tracks. We take into account the mosaic of crystals (e.g., we use for Si, Ge and HOPG crystals the mosaic with FWHM = 0.02°, FWHM = 0.02° and FWHM = 0.2°, respectively).

Fig.7 shows the simulation results of the radiation intensities calculated for the experimental condition accounting the efficiency of radiation detection by the Si detector.

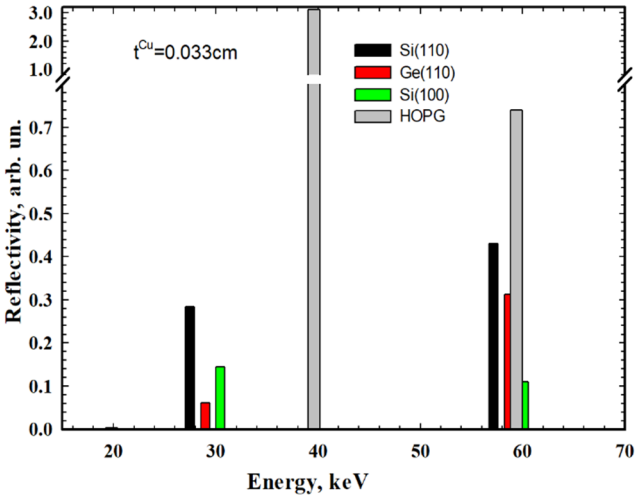

Fig. 7 Simulation results of the radiation intensity for different diffraction orders for Si(220), Si(400), Ge(220) and HOPG (0002)

Simulation results of the reflectivity of a number of crystals accounting the absorption of radiation by a water layer of 50 mm thick are illustrated in Fig.8.

There is a quality agreement between experimental data (see Fig. 5) and simulation results (see Fig. 6) when the radiation intensities in the first and second peaks of corresponding crystals are compared. Fig. 8 illustrates the simulation results of the radiation intensities for different diffraction orders for Si (220), Si (400), Ge (220) and HOPG (0002) when X-rays pass through a 50 mm water layer. We obtain the highest radiation intensity for Si crystal on the planes of (110) series.

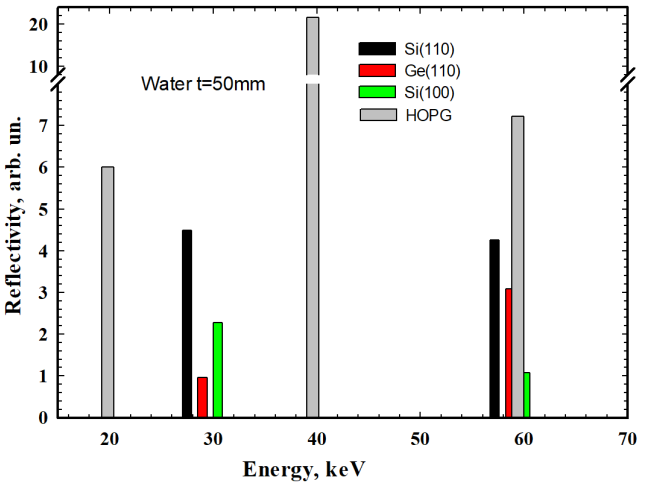

Fig. 8 Simulation results of the radiation intensities for different diffraction orders for Si (220), Si (400), Ge (220) and HOPG (0002) when X-rays pass through a 50 mm water layer

V. SUMMARY

Simulation results agree with the experimental data. They point out that the spectrum, which includes two monochromatic lines with approximately equal intensity, can be achieved using the proposed scheme based on the radiation diffraction from the X-ray tube. The application of Si crystal with the (110) plane orientation is preferable.

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