Optimized X-ray spectra for multiphase-flow measurements

M.C. Clarijs, V.R. Bom, Z.I. Kolar, C.W.E. van Eijk, Interfaculty Reactor Institute, Delft University of Technology, Mekelweg 15, 2629 JB, Delft,NL
clarijs@iri.tudelft.nl, vb@iri.tudelft.nl
J. Frieling, A.M. Scheers, A.E.J. Reimerink, Shell International Exploration and Production B.V, Rijswijk, NL

Abstract We present different X-ray set-ups that have been studied with the EGS4 Monte Carlo code for the purpose of multiphase metering of an oil/saline water/gas mixture. Determination of the different fractions in such a mixture should be performed using mono-energetic radiation, necessitating use of characteristic X-rays. The different set-ups under study combine generation of secondary fluorescence with elimination of the primary X-ray continuum. A Reflection fluorescence geometry is suitable for generating spectra with sufficient peak intensities on a low continuum background. Feasibility of application in MEXA is determined by the accuracy of determination of the mono-energetic photon intensities before and after the multiphase-flow.

Introduction

The purpose of the project is to design and develop a new type of instrument that can measure the individual flowrates of oil, water and gas in a multiphase flow environment through pipelines. Most multiphase flow meters consist of a total fluid (water, oil and gas) flowrate measurement combined with oil, water and gas fraction measurement, plus the salinity of the production water.

The multiphase composition meter that is currently being developed is based on the measurement of gamma or X-ray absorption. Although this technique seems to be technically superior to all other techniques applied in multiphase flow composition measurement, there is one huge disadvantage and that is that all commercially available gamma or X-ray absorption based multiphase flow meters, at present, use permanent radioactive sources to generate the gamma or X-rays. In particular the licensing procedures, the transportation, the on-site safety, the disposal and the psychological barriers that accompany the use of radioactive sources seriously hinder the application. In some cases the application of multi-phase meters with a radio-active source is even not possible.

In the present project we consider application of an X-ray tube. The main safety advantage is that the X-ray equipment can be switched off. Furthermore, licensing procedures for X-ray equipment are far more relaxed than those for radioactive sources.

1 This project has been made possible by the BTS-support of the Ministry of Economic Affairs (Ministerie van Economische Zaken).
**DEGRA and MEXA**

At present, multiphase-flow measurements are performed with Dual Energy Gamma Ray Absorption (hereafter: DEGRA), where two energies are used to determine the oil ($o$), water ($w$) and gas ($g$) fractions in the multiphase flow. A Multiple Energy X-ray Analysis system (hereafter: MEXA) makes use of three different energies to determine an extra parameter, the salinity of the water ($s$).

Determination of the different components in the multiphase flow is performed by measuring the attenuation of X-rays through the absorber:

$$I(E_1) = I_v(E_1) \cdot e^{-\left(\frac{\mu(E_1)_w}{\rho} \cdot \rho_w \cdot \alpha_w + \frac{\mu(E_1)_o}{\rho} \cdot \rho_o \cdot \alpha_o + \frac{\mu(E_1)_g}{\rho} \cdot \rho_g \cdot \alpha_g\right) d}$$

$$I(E_2) = I_v(E_2) \cdot e^{-\left(\frac{\mu(E_2)_w}{\rho} \cdot \rho_w \cdot \alpha_w + \frac{\mu(E_2)_o}{\rho} \cdot \rho_o \cdot \alpha_o + \frac{\mu(E_2)_g}{\rho} \cdot \rho_g \cdot \alpha_g\right) d}$$

$$\alpha_w + \alpha_o + \alpha_g = 1$$

$$\begin{bmatrix}
\ln I_w(E_1) & \ln I_o(E_1) & \ln I_g(E_1) \\
\ln I_w(E_2) & \ln I_o(E_2) & \ln I_g(E_2)
\end{bmatrix}
\begin{bmatrix}
\alpha_w \\
\alpha_o \\
\alpha_g
\end{bmatrix} = 
\begin{bmatrix}
\ln I(E_1) \\
\ln I(E_2)
\end{bmatrix}$$

Absorption of X-rays at two different energies $E_1$, $E_2$ is given by exponential attenuation in the different components in the mixture, denoted by indices $o$, $w$ and $g$. The intensity for energy $E_i$ after absorption is given by $I(E_i)$, and

$$I_w(E_i) = I_v(E_i) \cdot e^{-\frac{\mu(E_i)_w}{\rho} \cdot \rho_w \cdot d}$$

is the intensity for energy $E_i$ when the pipe is filled with water. Similar equations hold for oil and gas. $I_v$ refers to the intensity after absorption through the vacuum pipe.

Likewise, the MEXA algorithm that includes measurement of the salinity can be described by

$$\begin{bmatrix}
\ln I_w(E_1) & \ln I_s(E_1) & \ln I_o(E_1) & \ln I_g(E_1) \\
\ln I_w(E_2) & \ln I_s(E_2) & \ln I_o(E_2) & \ln I_g(E_2) \\
\ln I_w(E_3) & \ln I_s(E_3) & \ln I_o(E_3) & \ln I_g(E_3)
\end{bmatrix}
\begin{bmatrix}
\alpha_w \\
\alpha_o \\
\alpha_g
\end{bmatrix} = 
\begin{bmatrix}
\ln I(E_1) \\
\ln I(E_2) \\
\ln I(E_3)
\end{bmatrix}$$

$$\alpha_s = f \cdot \alpha_w$$

The last expression describes constant salinity in the water, a valid assumption for a time period in the order of hours, whereas the other fractions vary on a time scale of seconds.
Energy optimalization

A study into the optimum MEXA X-ray energies showed some important results:

- optimum energies are given by two low energies (e.g. 20, 40 keV) and one higher energy (60 keV) to determine the total density of the mixture. Above 60 keV the mass absorption curves of all mixture components coincide.

- the energies used are from mono-energetic X-rays. Use of narrow energy bands around a central energy value leads to large deviations in the determined fractions.

- photon intensities for the different mono-energetic peaks should be very accurately known, before and after the pipe absorber.

Necessary use of mono-energetic radiation in combination with an X-ray tube leads to a logical choice of a set-up that is based on fluorescence. The primary X-ray continuum consists of the Bremsstrahlung spectrum and additional fluorescence peaks. Since the X-ray continuum is not useful for MEXA analysis, we studied set-ups that separate continuum radiation from (secondary) fluorescence.

Since emission of fluorescence from secondary targets involves loss of photon intensity, set-ups should be compact, allowing filters to be placed close to the anode. Therefore, the choice was for transmission X-ray tubes, with an integrated anode and end-window. The studies on the various set-ups were performed with the EGS4 Monte Carlo code.

Transmission fluorescence X-ray set-up

This set-up is based on the conversion of primary continuum radiation of a W anode into secondary fluorescence in filters by means of photo-ionization followed by fluorescence. The filters (Sm and Ag foils with Kα fluorescence radiation of respectively ~40 and ~20 keV) were placed close to the anode, to ensure a high conversion yield. The 60 keV energy was provided by fluorescence of the W anode itself.
An additional restriction for the use of an X-ray tube was the power, that should not exceed ±50 W. It was concluded that fluorescence yields in all set-ups were well above the acceptable count rates in the detector of ±1 x 10^5 s^-1 (full spectrum). The bottle-neck for the set-up is the primary continuum background that proved to be too high for accurate MEXA analysis. This is illustrated by the following picture:

**Reflection fluorescence X-ray set-up**

A reflection fluorescence X-ray set-up as shown in the following figure is based on geometrical separation of the primary continuum and the secondary fluorescence. Three different foils (Ag, Sm and W from left to right) deliver fluorescence radiation that is detected under a 90 degrees angle with respect to the primary continuum. A gold anode ensures somewhat higher photon intensities than a tungsten anode. The anode thickness is only ±10 µm thick, enough to stop the 100 keV electrons and to keep photon intensities as high as possible.
The resulting spectrum shows a low continuum contribution whereas secondary fluorescence intensities are still high enough. The peak/continuum or signal-to-noise ratio is ~ 1000 for the reflection fluorescence geometry vs. ~ 10 to 100 for the transmission fluorescence geometry. Feasibility of MEXA analysis with this spectrum is determined by accurate determination of peak intensity before and after the pipe absorber. Detector effects such as escape peaks, energy resolution and other artefacts have not been considered in the simulation study.

Conclusions

Multiphase-flow measurements using MEXA must be based on use of mono-energetic radiation. Use of a transmission-type X-ray tube provides the opportunity to generate secondary fluorescence in foils, that is separated from the primary X-ray continuum by measuring under a 90 degrees angle. Photon intensities are sufficiently high. Feasibility of application in MEXA depends on the accuracy of determination of the mono-energetic photon intensities before and after the multiphase-flow.

References:

