Void Fraction and Flow Regime Determination by Low-Energy Multi-Beam Gamma-Ray Densitometry

E. Åbro[1] and G.A. Johansen[2]

[1] Christian Michelsen Research AS, P.O. Box 6031, N-5020 Bergen, Norway
[2] University of Bergen, Department of Physics, Allègaten 55, N-5007 Bergen, Norway.

Abstract *– Gamma-ray densitometry is a frequently used method for non-intrusive measurement of the void fraction in two- and multi-phase gas liquid pipe flows. Here it is demonstrated how a multi-beam configuration using a low-energy gamma-ray source and several detectors, enables the void fraction to be determined almost independent of the flow regime.*

An experimentally verified EGS4 Monte Carlo simulation has been developed of the multi-beam gamma-ray densitometer. This is an efficient tool in developing the densitometer as detector responses to different void fractions and flow regimes easily are generated. The simulations cover the full range of void fractions with homogeneous, annular and stratified flows. The model has also been applied to generate training data for a neural network which then was tested with experimental data. This has been done for a variety of detector positions in order to optimise the geometry of the multi-beam densitometer. Polypropylene phantoms (density = 0.91 g/cm^3) were used to represent oil in these experiments in order to have reliable and accurate references.

By using experimental data as input to the neural networks, the void fraction was determined with an error of 3% regardless of the flow regime. The flow regimes were successfully recognised in all cases studied here, meaning that the system also provides tomographic information.

1. INTRODUCTION

The oil and gas production industry has a need for accurate measurements of the oil and gas fractions in pipelines. Improved production techniques have made it economically feasible to produce from smaller (marginal) reservoirs by using subsea and even downhole production units.

With several production lines running into a production separator on the platform, it is impossible to measure the gas fraction in each line. At present, the flow is separated and then the fractions are measured. A test separator is used to separate the flow and then the individual phases in each production line are measured at sequentially. Usually, turbine meters and orifice plates are used to measure the oil and gas flows, respectively. One disadvantage of this technique is that test separators are large units and space costs on a production platform are high.

2. MULTI-BEAM GAMMA-RAY DENSITOMETRY

Measurements of the void fraction, i.e. the gas fraction, with traditional single beam densitometers are strongly dependent on the flow regime. This is because the content of the measurement volume often is not representative for that of the total pipe cross section. In the system presented here this is overcome by using several beams from one low energy source; ^{241}Am with 59.5 keV gamma-ray emission. The low energy also enables compact design due to reduced shielding requirements (2 mm of lead) and compact detectors. These are important aspects with regard to future subsea and down-hole fluid flow measurement applications. A possible design of a compact gamma-ray densitometer integrated into the pipe wall, is shown in Figure 1.

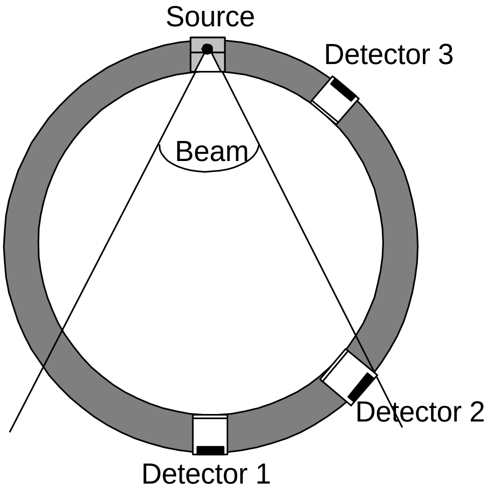

Figure 1. Possible design of a compact low-energy multi-beam gamma-ray densitometer.

The dominant interaction mechanisms for low-energy photons are the photoelectric effect and Compton scattering. For the photoelectric effect the interaction probability is proportional to the atomic number to the power of 4 - 5. For Compton scattering, the interaction probability approximately proportional to the density of the absorber.

Photon scattering is often regarded as an undesirable effect in gamma-ray transmission measurements, since it complicates the interpretation of the results. Build-up, i.e. the extra contribution to the measured transmission intensity from scattered radiation, has to be accounted for, particularly if wide-beam measurement configurations are used [3]. In fluid flow fraction measurements, however, it is possible to take advantage of this effect since it effectively means that the gas-liquid distribution outside of the actual measurement volume affects the result [7]. This may to some extent be regarded as a geometrical measurement averaging over the pipe cross-section, especially for backscattered radiation measurements where there is no contribution from direct transmission.

With several detectors installed over the same pipe cross-section both transmitted and scattered radiation can by measured in several positions. The energy of scattered photons depends on the scattering angle. Since the interaction probability is much higher in oil than in gas, scatter is mainly generated in oil. There is thus a relationship between the detected radiation energy and intensity, and the distribution of oil and gas inside the pipe. This is, however, difficult to predict analytically because of the random nature of radiation transport though matter. A Monte Carlo simulation model has been developed and implemented in order to study transmitted and scattered photons over the pipe cross-section [8].

3. THE MODELS

A Monte Carlo simulator for radiation transport through matter basically consists of three parts: A data base containing all the stopping efficiency data for all the components or materials involved. Then there is the simulation code which by generating random numbers calculates directions, path lengths, scattering angles etc. for each photon emitted from the source, and all secondary radiation generate. Once all the radiation energy of one photon (and its secondary radiation) is deposited or accounted for, its history is said to be terminated and the procedure is repeated for a new photon. The third part of the simulator is the simulation model which is the definition the system`s geometry. i.e. which materials are involved and the location of these.

Here three simulation models were developed to represent homogeneous, annular and stratified flows as shown in Figure 2. It was necessary to develop one model for each type of flow regime because of the difference in geometry. Each model includes a variable, which allows the void fraction to be varied from 0 to 100%. Further details about the models can be found in [8].

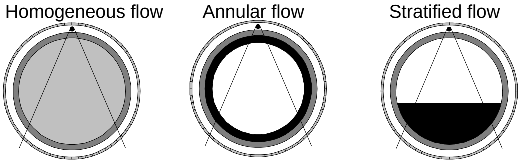

Figure 2. Models with different flow regimes. Black and white fields represent liquid and gas, respectively [8].

For homogeneous flow 11 simulations were performed, covering void fractions from 0% to 100%. Since void fractions of 0% and 100% with annular and stratified flows are identical to that of homogeneous flow, 9 simulations were performed for stratified and annular flows each, covering void fractions from 10% to 90%. The number of simulated histories are $5.0 \cdot 10^6$, and with a 14 mCi ^{241}Am source it can be shown that it corresponds to 0.60 seconds of photon emission of the real source.

With the reliable references of void fraction and flow regimes it is easy to verify if the neural network output determine the correct void fraction and flow regime regarding to the measurements of the phantoms in Table 1.

4. EXPERIMENTAL SETUP

An aluminium pipe was made to investigate the feasibility of the multi-beam gamma-ray low-energy densitometry principle. Polypropylene phantoms (density = 0.91 g/cm^3) were used to represent oil in these experiments in order to have reliable and accurate references. The density of the phantoms is higher than that of most oils, but is close enough to verify the principle. The inner and outer diameters of the pipe are 80mm and 90mm, respectively. A 14 mCi ^{241}Am (59.5 keV) source and a single eV A1361 CZT (CdZnTe) semiconductor detector were used in the experiments. The aluminium pipe, source and detector are mounted in a computer-controlled test platform where the angular positioning accuracy of the detector around the pipe is ±1° [6]. The multibeam configuration was then emulated by sequential measurements with the detector in 8° intervals around the pipe, from 52° near the source to 180° opposite the source. The use of phantoms ensured that the "flow regime" was fixed for all these measurements. Table 1 summarises the conditions for the measurements carried out here.

Void fraction [%]	Flow regime phantom
0	Homogeneous
20	Stratified
20	Annular
25	Annular
50	Annular
50	Stratified
56	Annular
70	Annular
80	Stratified
100	Homogeneous

Table 1. Void fraction and flow regime phantoms made for the experiments.

The detector read-out system consisted of an eV-550 preamplifier, a Tennelec TC244 amplifier and an Oxford PHA (Pulse Height Analyzer). This allowed the energy distribution of the radiation deposited in the detector at each position to be determined. A measurement time of 600 s was used for each of the detector positions.

5. EXPERIMENTAL RESULTS

Before studying the results from the multi-beam configuration it may be useful to look at the performance of a traditional single-beam densitometer using the same phantoms as listed in Table 1.

Figure 3 presents the void fractions calculated from transmission measurements with a 2" NaI(Tl) scintillation detector located diametrically opposite a 1 mCi ^{137}Cs (661.7 keV) collimated source. A steel cap with a Ø10 mm hole was used to collimate the PMT in order to minimise the contribution of scattered photons and to achieve an appropriate count rate.

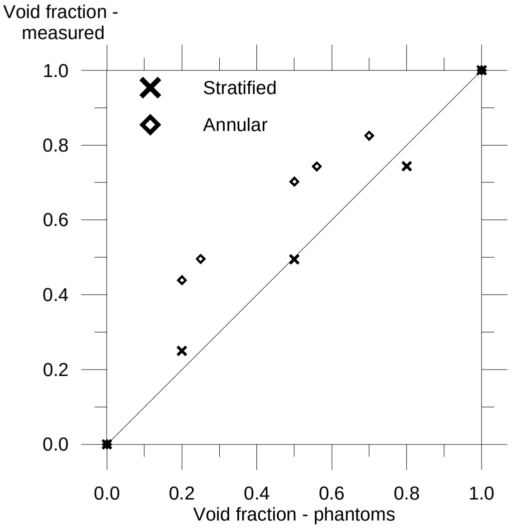

Figure 3. Measured void fraction versus true void fraction using conventional gamma-ray densitometer with 137Cs source. The solid line represents the ideal case with no deviation between true and measured void fractions [7].

The deviation between the true void fraction and the measured void fraction appears to be largest with the annular flow regime phantoms. This is in agreement with theory [7]. The relationship between measured intensity, I_{mix}, and the void fraction is:

$$a = \frac{ln\left(\frac{I_{mix}}{I_{oil}}\right)}{ln\left(\frac{I_{gas}}{I_{oil}}\right)} \qquad (1)$$

where I_{oil} and I_{gas} correspond to 100% oil and 100% gas, respectively. These are the calibration measurements. Equation (1) assumes that the contribution of scattered photons is negligible.

By using Equation (1) the void fraction can easily be calculated from measurements of transmitted radiation, provided the attenuation properties of each of the flow components are known from calibrations. However, for detector positions outside the direct beam, i.e. those measuring scatter only, there is no analytical expression for the void fraction as function of the measurements.

Figure 4 shows the raw data from the detector located at 52°. This is an example of the latter; the detector measures scatter only.

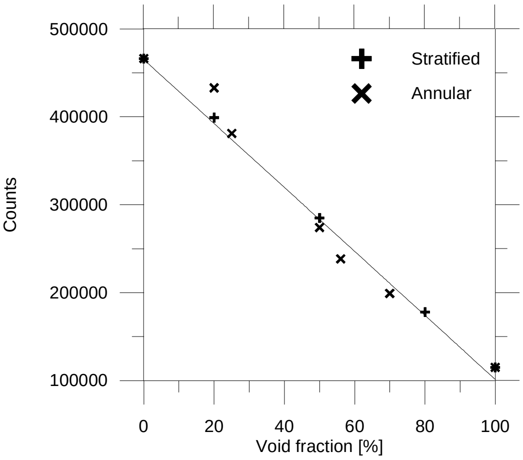

Figure 4. The measured number of counts in the full energy peak plotted against the void fraction with the detector located at 52° (the source is at 0°). The legends and the solid line represent the measured data and best curve fit, respectively [8].

At 52° the number of counts appears to be more or less inversely proportional to the void fraction. The relationship is almost linear for stratified flow.

In the following Equation (1) was used to calculate the void from measurements at several positions around the pipe, scatter measurements as well as transmission measurements. It was established that the average values of the calculated void fractions for detector positions at 180°, 140°, 68° and 52° had a very small discrepancy from the ideal linear relationship. Only scattered photons are detected in the detector positions at 68° and 52°.

This is demonstrated in Figure 5 and Figure 6 for annular and stratified flows, respectively. The measured void fractions at 180° are, as expected, similar to the data obtained by the traditional densitometer (Figure 3). In this position the measured void fractions with stratified flow phantoms are close to the true void fractions. At 68° and 52°, however, it can be seen that void fraction measurements of the annular flow phantoms are underestimated and are closer to the true void fraction than measurements made at 180°. It is interesting to note that at 68° and 52°, the measurements of annular flow phantoms are closer to the true void fraction than measurements of stratified flow phantoms.

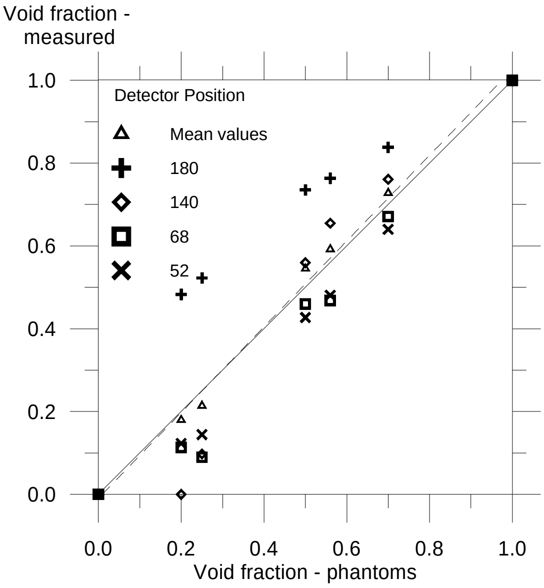

Figure 5. Measured void fraction versus true void fraction of the annular phantoms at several detector positions. The solid line represents the ideal case with no deviation between true and measured void fractions. The dashed line is the best curve fit of the mean values[7].

The data presented in Figure 5 and Figure 6 demonstrates the feasibility of using a multi-beam configuration to obtain results less dependent on the flow regime than what is possible with a single-beam system. The best fit line of the average data for all detectors has small deviations to the ideal line (which would occur with homogeneously mixed flow and a single beam transmission measurement).

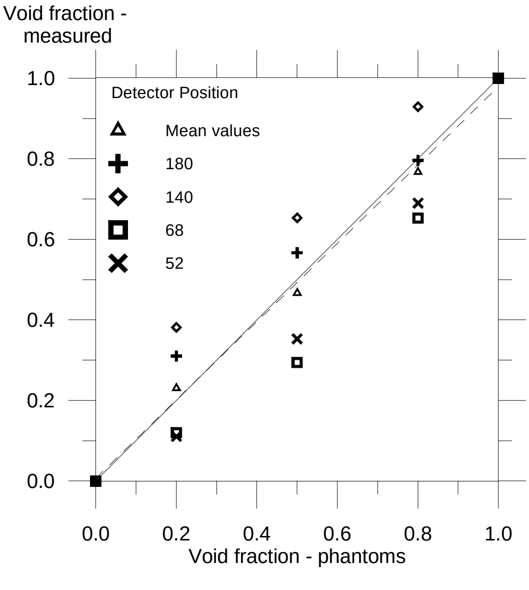

Figure 6. Measured void fraction versus true void fraction of the stratified phantoms at several detector positions. The solid line represents the ideal case with no deviation between true and measured void fractions. The dashed line is the best curve fit of the mean values [7].

It seems feasible to identify the type of flow regime by comparing the responses from the four detectors in the case of annular and stratified flows as presented in Figure 5 and Figure 6, respectively. But the spectral information recorded by each of the detectors is not fully utilised here.

For this reason a neural network has been trained by the simulated gamma-ray data and then used to analyse the measured spectra. (This has been an iterative procedure since the neural network also was applied to find optimal multibeam configuration.) The experimental conditions are accurately defined due to the use of the phantoms, making it easy to quantify the performance of the method.

For the multi detector configuration the average of 5 simulated examples was used as the training set. With 11 void fractions and 3 flow regimes, the total number of training examples is 33. By using the response from only one detector located at 180°, the average error was about 15% in the determination of the void fraction, regardless of the flow regime. With responses from three detectors, the average error was only 3% in the void fraction determination. In addition, all represented flow regimes used here were detected without error [8].

6. CONCLUSIONS

It has been shown that a multi-beam gamma-ray densitometer with four detectors can be used to determine the void-fraction accurately and independent of the flow regime.

The use of a neural network trained by simulated data enables the void fraction to be determined with an average error of 3% using data from a system consisting of three detectors. All flow regimes were detected without error.

This demonstrates how full utilisation of detector information and the use of a priori knowledge, can be applied to design a system of which the performance for specific tasks, is comparable to that of a full tomographic system with multiple sources and detectors.

REFERENCES

[1] *R Thorn, G A Johansen and E Hammer,* Recent developments in three-phase flow measurements, Meas. Sci. Tech. **8** (1997) 691-701.

[2] *P S Harrison, G F Hewitt, S J Parry and G L Shires*, Development and testing of the “Mixmeter” multiphase flow meter, Proceedings of North Sea Flow Measurement Workshop, 1995.

[3] *H Linga*, Measurements of two-phase flow details, Dr.ing. Thesis, Norwegian Institute of Technology, University of Trondheim, 1991.

[4] *E Åbro, G A Johansen and H Opedal*, A radiation transport model as a design tool for gamma densitometers. Submitted for publication 1998.

[5] *H Opedal*, Integrated gamma densitometer and venturi meter for liquid phase measurements (in Norwegian) M.Sc thesis, University of Bergen, 1997.

[6] *G A Johansen, T Frøystein, H Pedersen, B McKibben*, A Flexible Test Platform for Investigating Gamma-Ray Tomography Geometries and Applications, Proceedings of: Frontiers in Industrial Process Tomography II, Delft, The Netherlands, April 9-12 1997.

[7] *E. Åbro and G.A. Johansen,* Improved void fraction determination by means of multibeam gamma-ray attenuation measurements, Flow Meas & Instr, In press 1998.

[8] *E. Åbro, V.A. Khoryakov, G.A. Johansen and L. Kocbach*, Determination of void fraction and flow regime using neural network trained on simulated data based on gamma-ray densitometry. To be published, 1998.