Multibeam gamma-ray measurements and electrical tomography for improved multiphase flow metering

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Introduction

Today's multiphase flow meters (MPFM) are dependent on some degree of flow mixing or a predictable flow-regime. The most common way of installing the flow meter is with vertical upward flow, where the flow is assumed to be axis symmetric. Often an upstream T-bend is used. The different measurements in the MPFM are interpreted and used for parameterisation of the flow based on a relatively simple flow model. Flow rates of the individual flow components are calculated based on this. Roxar and the University of Bergen (UoB) have over many years investigated measurement systems that gives information on how the flow components are distributed over the flow cross-section. These are multibeam gamma-ray attenuation measurements and electrical tomographic measurements. The new measurements can be used for more detailed flow models and improved measurement accuracy for the standard vertically installed meter and can also enable non-vertical installation of the MPFM, e.g. for dowhole applications.

Modelling multiphase flow

The flow model used by the Roxar flow meter was developed in the 1990s and has been continuously improved based on flow loop tests and field experience [1, 2]. The general model is valid for flow-regimes experienced in vertical upward flow, ie. bubble, churn or slug flow, by the introduction of voxel based parameterisation, as illustrated in Figure 1.

The model is axis symmetric and divides the flow into three different voxels. For each voxel there are a number of parameters describing size, composition and velocity. The parameters describing each voxel are not input parameters, but are measured in real time, thus adapting the flow model according to changing flow regimes. In a bubble flow, the size of voxels 2 and 3 (referring to Figure 1) will be close to zero, but increasing as the flow enters the churn or slug flow regions. In principle this model will also cover annular flow, when voxel 1 is zero, however in this case the cross-correlation method (cross-correlation of capacitance measurements for two measurement planes along the flow) cannot be used for measuring the velocity of the large bubble voxel (voxel 2). Details on the flow model have been improved over the years. An example is the gas fraction for voxel 1, where it has turned out that a higher gas fraction towards the centre of the flow gave a more correct model [3].

The model has proven to provide good measurement accuracy for multiphase flow measurement. However, there are obvious limitations to the model. The general model is a very simplified description of the complex multiphase flow and installation effects might cause the flow not to be axial symmetric. By using new measurements that can provide more detailed information on how the liquid and gas are distributed over the flow cross-section it is possible to take into use a more complex flow model that is closer to the real flow, and not necessarily axis symmetric.

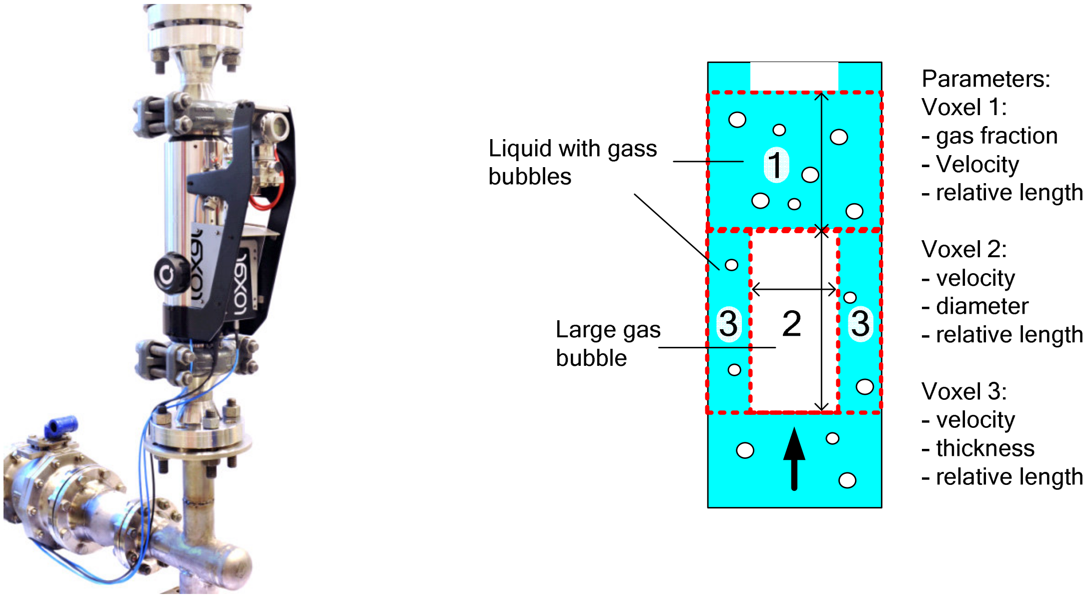


Figure 1. Left: Roxar MPFM 2600 installed vertically after T-bend. Right: model for slug flow

Tomography used in multiphase flow metering

Tomography refers to imaging the cross-section of an object by some measurement principle. Examples of this are medical tomography by CT (x-rays) or MRI (Magnetic Resonance Imaging). In medical tomography it is important to achieve precise high-resolution images of the body part to be imaged. The requirement for tomography used in multiphase flow measurement is quite different. Here the aim is to be able to do precise measurements of oil, water and gas flow-rates. Reliability and robustness of the measurement system are also important properties for a multiphase flow meter. It is thus beneficial to have a relatively simple measurement system that does not rely on a large number of detectors. A full tomographic image of the flow cross-section is thus not necessarily the aim. The combination of only a few measurements can be sufficient to obtain new information that will provide a better flow model and improved measurement accuracy. The word ***tomometry*** [6] has been introduced for this measurement concept. This is defined as cross-sectional metering of process parameters using multiple measurements.

These measurement concepts are required both for improving measurement accuracy at vertical flow and for non vertical installation this type of measurements are crucial. Roxar has in collaboration with UoB and CMR (Christian Michelsen Research) investigated non vertical flow installation, and first flow-loop tests on horizontal and inclined flow were conducted in 2001 [4, 5]. Tomographic techniques for multiphase flow has also been investigated earlier [6].

A number of flow loop tests with non-vertical installation have been carried out during the development of the Roxar downhole flow sensor system. This year a flow loop test with the Roxar MPFM2600 in horizontal and inclined installation was also carried out. In most of these tests the UoB gamma-ray tomograph [7, 8] was used as a reference instrument. This instrument consists of 5 Am-241 nucleonic sources and 85 semiconductor detectors. The time-resolution for the tomograms used in this work is 10ms. Figure 2 show a cross-sectional drawing of of the gamma-ray tomograph. The tomograph was installed on an aluminum pipe with inner diameter of 82mm.

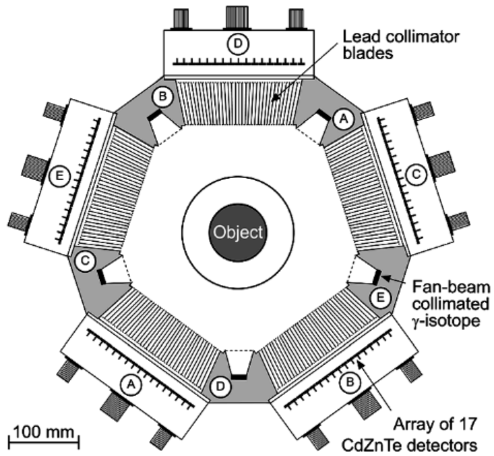


Figure 2. UoB gamma-ray tomograph.

The UoB gamma-ray tomograph is a unique reference instruments that opens for the possibility to study details in the multiphase flow regimes. An example of this is shown in Figure 3. The quality of the images are somewhat reduced close to the pipe wall due to a few detectors failing. In these tomograms the linear back-projection algorithm was used. This figure show that a real slug-flow is more complex compared to the theoretical model shown in Figure 1. Based on the tomograms a more advanced gas distribution function can be derived.

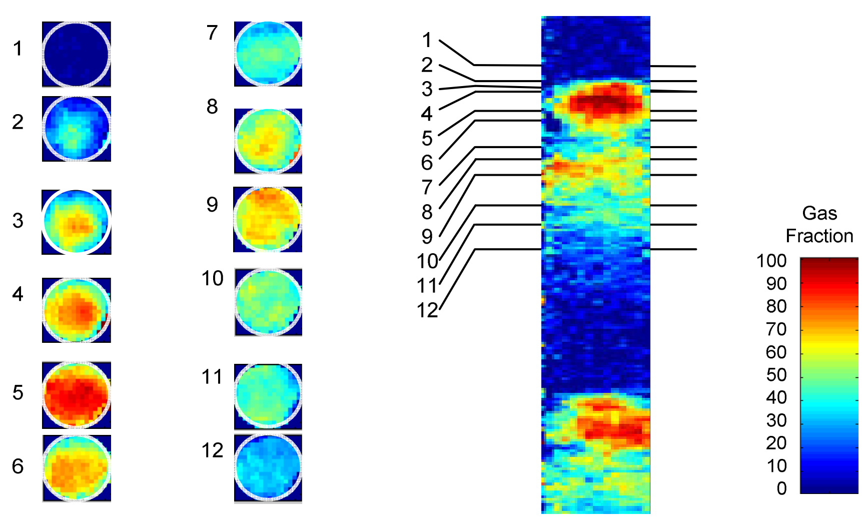


Figure 3. Tomograms and timeseries plot from one of detector sections of the gamma-ray tomograph. Time resolution 10ms. length of the time-series plot is 2.5s. The inner diameter of the pipe is 82 mm. (Flow-rate oil: 20m^3/h and gas 10m^3/h) .

Both the reference tomograph and flow instrument to be tested were installed in a tilt-section in the flow loop (Figure 4). The section can be tilted so that different inclination angles, from 0° (horizontal flow) to 90° (vertical flow), are achieved. Flexible hoses are connected at inlet and outlet of the tilt section. The time-series plots in Figure 4 show how the flow-regimes for vertical, horizontal and 45° inclined flow.

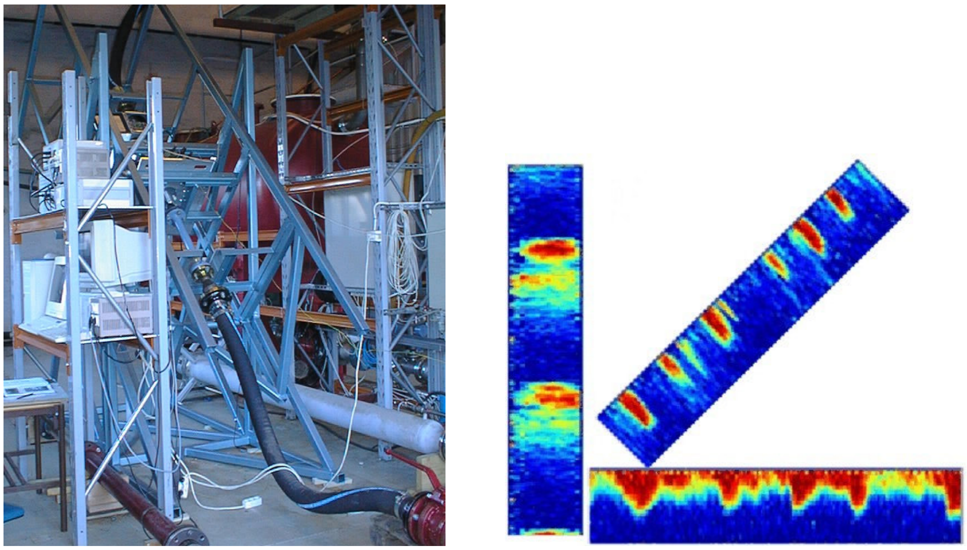


Figure 4. Left: the tilt-section at the CMR flow loop. Right: time-series plots of measurements from the gamma-ray tomography at horizontal, vertical and inclined (45°) flow. The length of the time-series plots is about 3s. (Flow-rate oil: 20m^3/h and gas 10m^3/h)

Electrical capacitance tomography in the Roxar MPFM2600

Electrical capacitance measurements are frequently used in multiphase flow metering. By measuring the capacitance between two electrodes the permittivity of the flow medium is found. The relative permittivity of gas, oil and process water is about 1, 2.2 and 70, respectively. This measurement is used for finding the water fraction in the Roxar MPFM. A capacitance sensor is also sensitive to the oil in a two-phase gas/oil flow. If the flow is water continuous then the electrodes will be short-circuited and it is not possible to do capacitance measurements. It is however possible to do electrical resistance tomography in water-continous flow. Cross-sectional images will then be based on resistance measurements between the different electrodes.

The Roxar MPFM2600 has two measurement planes for electrical flow measurement. One of the planes has the traditional two-electrode geometry also used in previous Roxar MPFMs, and the other plane has 6 electrodes, which can be used for capacitance or resistance tomography. In this paper only results from capacitance tomography are included.

The capacitance tomograms are based on the measurement of permittivity is along the electric fields from one electrode to another (Figure 5). The shape of these field lines depend on properties of the flow components and how the components are distributed over the flow cross-section. This type of flow imaging is called softfield imaging. Obtaining a precise reconstruction of the flow cross-section is thus more challenging compared to gamma-ray tomography where the sensing beam is a straight line from the source to the detector. The limited number of electrodes also limits the image-resolution of the tomogram. A high-resolution image of the flow cross-section is however not the aim for this type of tomography. The aim is to be able to find sufficient information to be able to compensate for flow-regime effects, and improve measurement accuracy of the flow-rates.

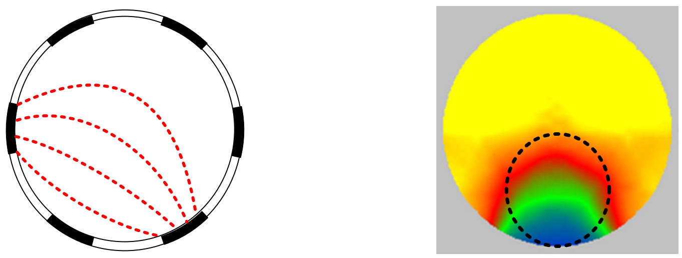


Figure 5: left: principle sketch of measurement geometry. Electric field lines between two electrodes are indicated. Right: static test with plexiglass rod placed in the measurement volume. The cross-section of the plexiglass is indicated.

Figure 5 illustrates the measurement volume and results from a static test. A plexiglass rod is inserted in the measurement cross-section. The capacitance is measured between each electrode, and with 6 electrodes we get 15 independent measurements. Due to the low number of measurements and the softfield nature of the measurement we do not get a clear image of plastic rod. The image does however provide sufficient information to locate the position and approximate size of the plastic rod. The algorithm used here is linear back projection. More advanced iterative reconstruction algorithms would give a better tomogram.

Tomograms of the flow are shown for horizontal, 45 degree inclination and vertical flow, both for the MPFM2600 capacitance measurements and for the gamma-ray tomograph. The images for the two measurement systems are not recorded at the exact same time. The figures clearly show that the MPFM2600 meter is able to identify the flow-regimes resulting from different inclination.

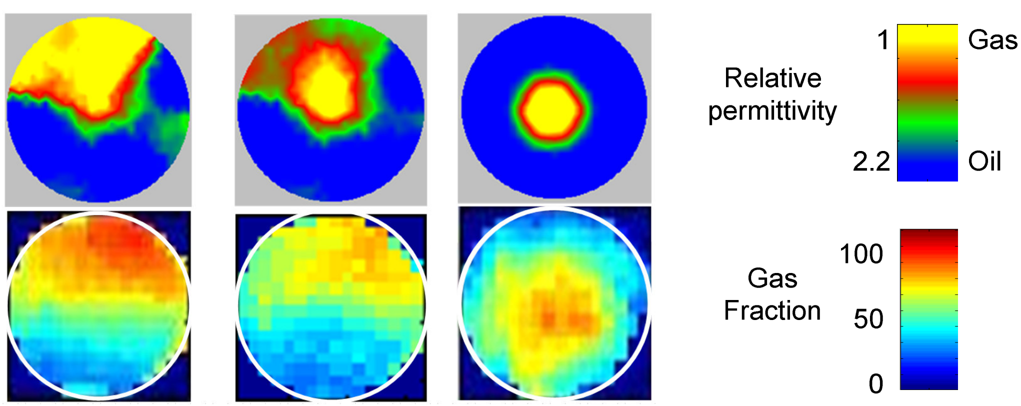


Figure 6: Flow test results. Above: series of tomographic measurements with MPFM2600. Below: Tomograms recorded with the UoB gamma-ray tomography. (Flow rate gas: $10m^3/h$, oil: $20m^3/h$) . The measurement time is about 10ms for both systems.

The traditional flow density gauge based on gamma-ray attenuation uses only one beam which is aligned through the centre of the pipe. The sensor will only measure the gas fraction along the measurement beam. For vertical installation the time-average gas fraction will be higher in the centre of the flow. This is due to the fact that large gas-bubbles tend to be located in the centre of the pipe. The effect increases with increasing gas fraction and partly also with flow-rates. A beam through the centre will thus measure a gas fraction that is higher than the average gas fraction over the whole flow cross-section. This can be corrected for by using a flow model that predicts the gas distribution over the flow cross-section. Based on the model illustrated in Figure 1 it is possible to compensate for this by finding the time fraction with homogenous flow vs time fraction with annular flow. When these time fractions are found then the time-averaged gas fraction measurement can be corrected. If the time-response of the gamma-ray measurement is sufficiently fast then the time periods with large gas bubble can be found based on the gamma-ray measurements alone [9]. A fast time response for the gamma-ray measurements requires high source activity and a fast detector. Often this is not practical and it is better to find the gas bubbles by other measurements, such as capacitance.

Capacitance or resistance measurements with more than two electrodes provide more detailed information on how gas and liquid are distributed over the flow cross-section. This can be used for correcting the gas fraction measurement based on single beam gamma-ray attenuation. Figure 7 show an example of how the gas/liquid distribution will cause different beam attenuation and thus measurement error if not corrected for.

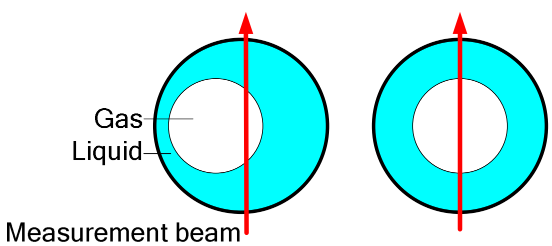


Figure 7. The gas fraction measured by using a single gamma-ray beam through the flow centre relies on a known gas/liquid distribution.

A 4-electrode downhole capacitance sensor

For the Roxar downhole capacitance sensor it is important to be able to measure horizontal flow or flow with different inclination angles. This means that a range of different flow-regimes can be expected, including stratified flow. A capacitance sensor with more than two electrodes is required for this. If there is a long distance with horizontal flow and low flow-rate then it is possible that a stratified flow-situation as illustrated in Figure 8 could occur. The 4-electrode sensor will not be able to produce a tomographic image of the flow. However, the sensor can detect that there is a short circuit between electrodes 2 and 3 which indicates water continuous flow, and there will be a permittivity between electrodes 2 and 4 indicating oil and finally between electrodes 1 and 4 the permittivity will indicate gas. The sensor will thus be able to find that there is a stratified flow with the presence of oil, water and gas and by combining the different permittivity measurements it will be possible to find the height of the different phases and estimate the total fraction of the different phases over the flow cross-section. By combining the capacitance measurements with other available data such as readings from the Roxar downhole gamma-ray module and the tilt sensor it will be possible to get a more detailed understanding of the flow situation.

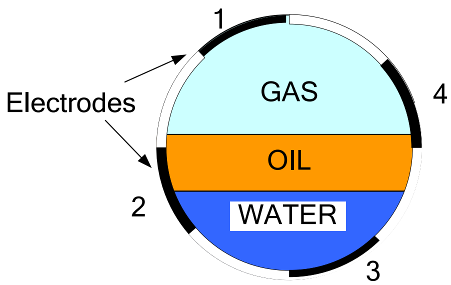


Figure 8. Principle sketch of downhole flow meter with stratified flow.

Multi-beam gamma-ray attenuation

As already described the flow-regime dependency of a single-beam gamma-ray densitometer can be reduced by combining the gamma-ray measurement with capacitance tomography and/or the time-averaged fraction modelling. Another way of compensating for non homogenous flow is to measure the attenuation along more than one gamma-ray beam. It is not practical to implement a full gamma-ray tomograph with a large number of beams in a multiphase flow meter. A less complex system with only one source and a few detectors (Figure 9) is better suited in a flow meter and also provides valuable new information although a tomographic flow image is not obtained. A number of flow loop tests on multibeam gamma-ray systems have also included detector-positions for the measurement of scattered radiation. [5, 9]. The results presented here are only from systems with three transmission beams.

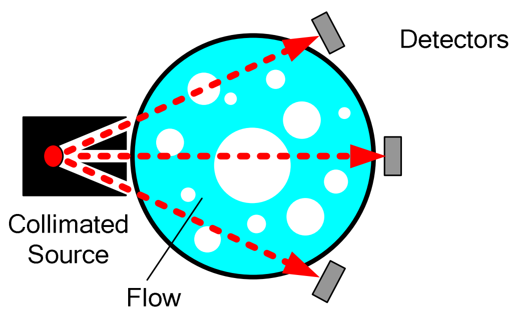


Figure 9. Principle sketch for the multibeam gamma-ray measurement geometry

By comparing measurements along a centre beam and along a beam closer to the pipe wall it is possible both to find flow-regime information and to find a more precise gas fraction for the whole flow cross-section [4]. For example, it will be possible to see an increase in the gas fraction along the centre-beam if there is more gas in the centre of the flow.

For vertical slug flow, it is expected to have large gas bubbles in the centre of the pipe (according to the model described in Figure 1). From the data recorded by the UoB gamma-ray tomograph it is possible to compare the measurement along different beams of the flow cross section. In Figure 10 the gas fraction along a centre beam of the gamma-ray tomograph and along beams closer to the pipe wall are plotted for a 6 second measurement period. The total gas fraction obtained by using all 85 beams is also plotted. It can be seen that the gas fraction is higher in the centre of the flow than close to the wall for each large gas bubble passing the measurement cross-section.

It is important to note that the gas fraction of the measurement cross-section might be different compared to the GVF (gas volume fraction) of the flow. The GVF is defined as the gas volume flow-rate relative to the multiphase volume fraction flow rate [10]. If the gas has higher velocity compared to the liquid (slip between gas/liquid) then the fraction of gas over the measurement cross-section will be lower than the GVF.

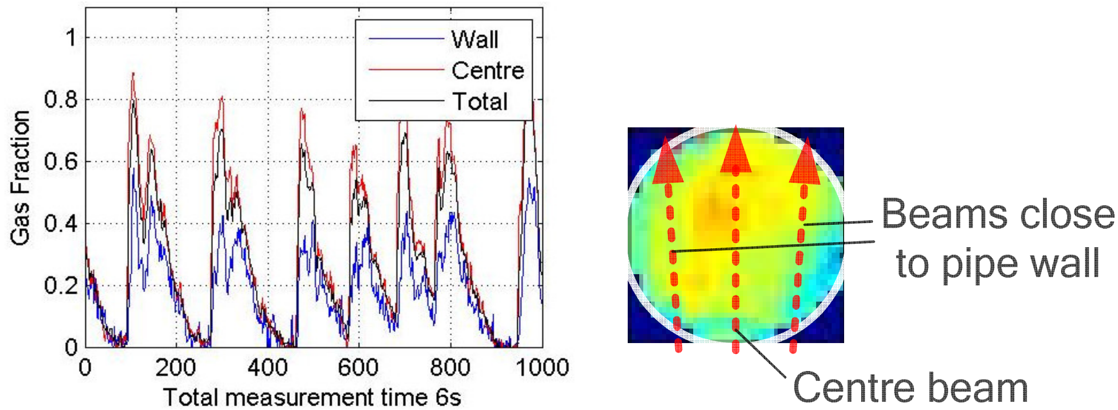


Figure 10. Gas fraction measured along centre beams, beams close to the wall and a weighted average of all beams. These are data from vertical slug (same as plotted in Figure 3).

When looking at the time-average gas fraction along the centre beam and the off-centre beam versus the gas fraction measured over the whole flow cross-section there is a systematic deviation. This can be seen in data from the tomograph plotted in Figure 11. The data are recorded for vertical upward oil/gas and total flow-rates ranging from 15 to 100m^3/h. There is a systematic over-estimation of the gas fraction when measured along the centre beam and underestimation when measured close to the pipe wall.

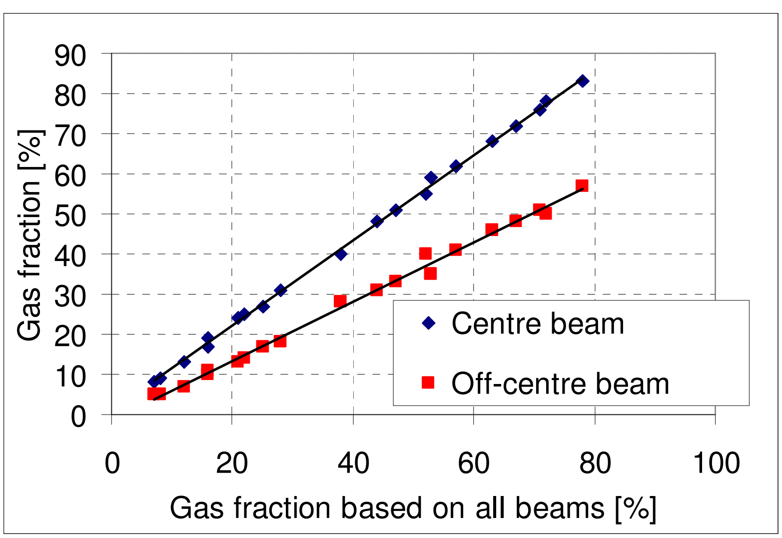


Figure 11. Gas fraction measured along centre beams and along beam close to pipe-wall (average gas fraction for the two beams illustrated in Figure 10) vs gas fraction for the whole cross-section.

It is expected that there is also a correlation between slip and the difference in gas fraction measured along the centre beam and the beam close to the pipe wall. When there are larger bubbles of gas in the centre of the pipe then it is likely that the gas will have higher velocity than the liquid. It is also expected that there will be more slip with increasing GVF. Both of these correlations are confirmed in Figure 12 show this correlation. The "measured slip" is the deviation between the gas volume fraction of the total cross-section measured by the gamma-ray tomograph and the GVF. This size is proportional to the slip ratio, which is the ratio between the two phase velocities.

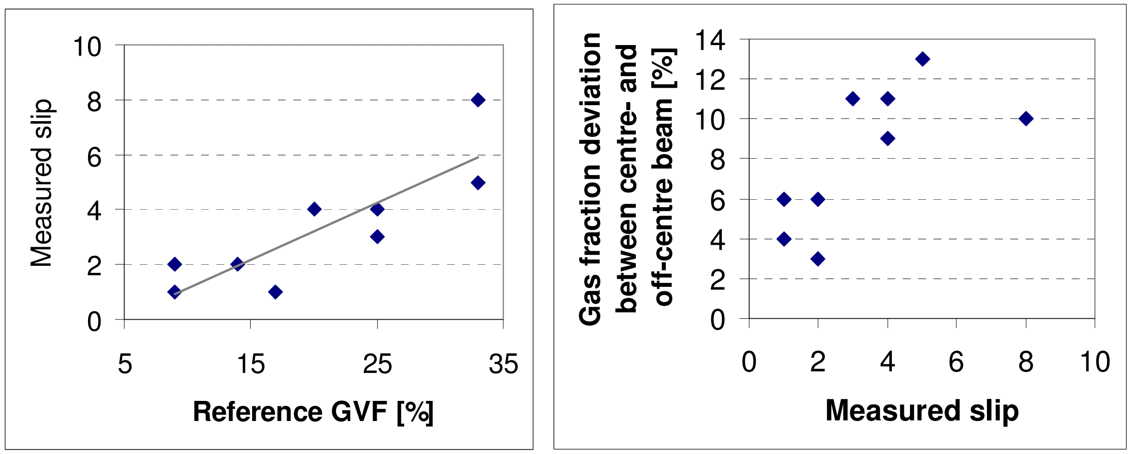


Figure 12. Left: measured slip vs reference GVF. Right: gas fraction deviation between centre and off-centre beam vs measured slip. The measurements are recorded with the gamma-ray tomograph on vertical flow. Water cut is 0 and 25.

The Roxar downhole gamma-ray sensor is a multibeam measurement system with three detectors and one Cs-137 source. The gamma-ray energy utilized is 662keV. The measurement geometry and sensor design is illustrated in Figure 13. The angular orientation of the sensor will not be known until the sensor has been installed, and it is thus important to be prepared for all possible orientations of the sensor. In Figure 13 three different orientations are illustrated. The response for the "top-bottom" orientation will be different compared to the "bottom-top" orientation with source under the flow or the orientation with the source on the side [7]. A range of flow loop tests have been carried out this multibeam sensor

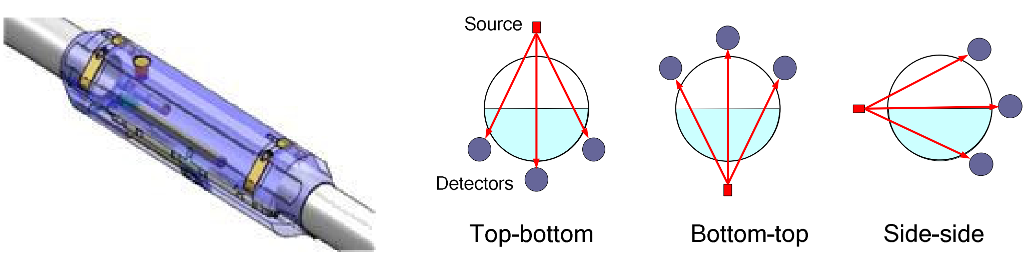
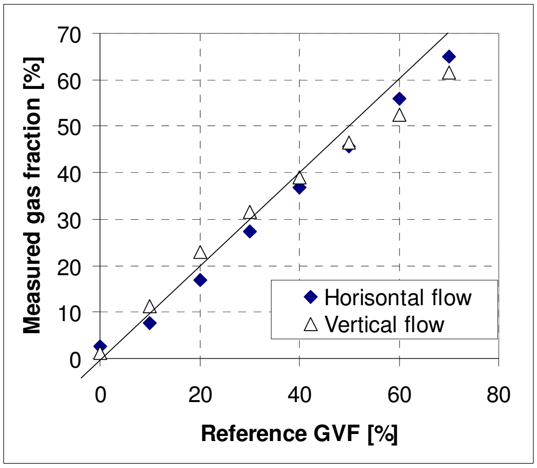


Figure 13. Left: The Roxar downhole gamma sensor. Right: measurement geometry for different rotations.

Results from flow loop tests on the downhole gamma sensor are shown in Figure 14. The data plotted are the results (average values) from flow loop test with about 100 measurement points for vertical and horizontal flow, flow-rates are in the range 30-50m^3 and WC ranges from 0 to 100%. At high GVF there is some deviation between the measured gas fraction and the rig reference GVF, this is expected and is caused by slip. For annular flow it is expected that there will be a higher gas fraction along the centre beam compared to the off-centre beams, and for stratified top-bottom flow the off-centre beam will measure the highest gas fraction. The left figure show the deviation between the gas fraction measured by the centre beam and the off-centre beams. We can see from the figure that the expected results are verified and that the measurements provide information on the type of flow-regime. The deviation between the centre beam and the beam close to the pipe wall is increasing with increasing GVF.



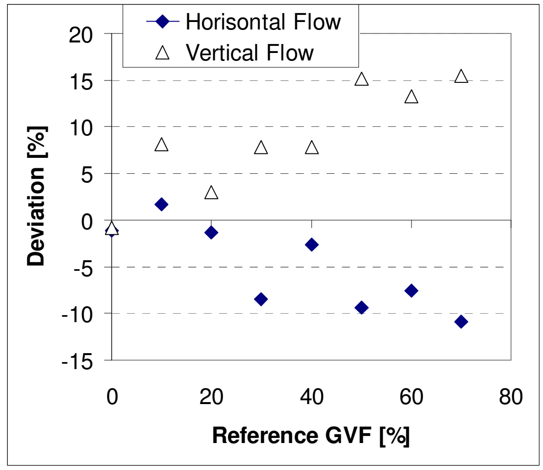


Figure 14. Measurement results for flow loop test at CMR for the Roxar downhole multibeam gamma-ray sensor. Right: Measured gas fraction vs rig reference GVF. Left: Deviation between measured gas fraction of centre beam and the beam close to the pipe wall vs rig reference GVF.

Conclusions:

The measurements presented show that electrical tomography and multibeam gamma-ray densitometery provides new information that can be used for improving the performance of a multiphase flow meter.

The 6-electrode capacitance measurement in the Roxar MPFM2600 can be used for finding the distribution of the flow components over the flow cross-section. This enables a more detailed flow model to be used, and thus improved measurement accuracy. Flow loop tests show that non-symmetric flow is identified.

The multibeam gamma-ray sensor concept enables improved gas fraction measurements and provides flow-regime information. This has been demonstrated in flow loop tests both with the UoB gamma-ray tomograph and the Roxar downhole multiple beam gamma-ray sensor.

References

[1] E. Dykesteen and Ø. Midttveit, "A flow-regime independent multiphase flow rate meter", North Sea Flow Measurement Workshop (1992)

[2] Ø. Midttveit " Development of signal interpretation models for multiphase flow rate metering of oil-water-gas flow" Dr scient. Theses, UoB (1996)

[3] E. Egner and O.P. Kalsaas, "Operational experience with multiphase meters at Vigdis", North Sea Flow Measurement Workshop (1999)

[4] S. A. Tjugum, B.T. Hjertaker and G. A. Johansen, "Multiphase flow regime identification by multibeam gamma-ray densitometry", Meas. Sci. Technol. 13 (2002) 1319-1326

[5] S. A. Tjugum "Dual Modality Densitometry" PhD thesis, Dept Physics, UoB, Bergen, Norway, (2003)

[6] Ø. Isaksen " A novel approach to reconstruction of process tomography data" Dr scient. Theses, UoB (1994)

[7] G. A. Johansen, T. Frøystein, B.T. Hjertaker, Ø. Olsen, "A dual sensor flow imaging tomographic system, Meas. Sci. Technol. 7 (1996) 297-307

[8] B. T. Hjertaker, S. A. Tjugum, E. A. Hammer, G. A. Johansen "Multimodality Tomography for Multiphase Hydrocarbon Flow Measurements" IEEE sensors journal, vol. 5 no.2, (2005)

[9] C Sætre, G. A. Johansen, S. A. Tjugum, "Tomographic multiphase flow measurement" paper for IRRMA8, Kansas (2011)

[10] S. Corneliussen, J. P. Couput, E. Dahl, E. Dykesteen, K. E. Frøysa, E. Malde, H. Moestue, P.O. Moksenes, L. Scheers, H. Tunheim, "Handbook of multiphase flow metering", rev. 2 (www.nfogm.no) (2005)