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MEASUREMENT STRATEGIES FOR DOWNHOLE MULTIPHASE METERING

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SUMMARY

There will be an increasing demand for multiphase subsea and downhole meters in the future. Both at the sea bottom and downhole the flow regimes in the production pipes or in the manifolds at the templates, may differ from the ideal homogeneous mixture. Further, in line mixers should be avoided to reduce pressure drops and maintenance costs.

The next generation multiphase meters will therefore call for flow regime independent and non-intrusive sensor systems. Since all sensor principles used in multiphase flowmeters today are highly dependent on the distribution of the components in the mixture, and thus make the measurement range limited, multi-sensor principles may be the solution to obtain better accuracy for larger ranges of component fractions and applications. Both the capacitance-, conductance-, microwave- and gamma-principles can be used in multi-sensor arrangement to provide cross-sectional information about the component distribution. Hence, the meter can be used at all types of flow regimes and at any position without mixers or separators.

INTRODUCTION

Today's multiphase flow meters either require flow mixing or installation on pipe lines where the flow regimes are known [1]. Some measurement principles are less dependent on the flow regime than others. Helical capacitance electrodes for fraction measurements perform, as an example, better than parallel electrodes when the flow regime varies. Multi-sensor instruments dividing the flow cross section into several smaller measurement volumes, have to the authors knowledge not yet been used in production processes in the oil industry. These instruments have many properties in common with industrial tomographs which have been used in multiphase flow rigs for testing and research purposes.

The multi-sensor principle will, without any doubt, be taken into use in the oil process industry as the reliability of this technology and the demand of more accurate multiphase metering increases. A multi-electrode or a multi-beam instrument can be used to measure the distribution of the liquid and the gas phases at non homogeneous mixtures and thus make the three phase meters independent of the flow regime. This is of particular interest in down hole metering where mixers can not be used and there is a need for flow regime independent meters.

The multi-electrode and multi-beam principle can also be utilized for improving the accuracy of multiphase meters top side or sub sea and thus make it possible to implement three phase meters for allocation purposes. Multi-sensor systems using capacitance- and gamma-technology, are being developed at the University of Bergen. The performance of these methods will be presented and discussed with respect to issues like measurement accuracy, flow regime dependency, reliability and physical constraints concerning installation and use.

HELICAL SENSORS

The problem of flow-regime dependency can, to a certain degree, be overcome using helical sensors (see Figure 1). In order to study the performance of this sensor, a three dimensional mathematical capacitance model has been developed at University of Bergen [2]. The model is based on the "Finite Element Method" (FEM) and Poison's equation. Using this model it is possible to simulate how the capacitance for different sensors varies with changes in flow parameters including water-fraction, void fraction, permittivity of the flow components, flow regime types and distributions and changes in sensor geometry and design. The model has been verified against measurements on different types of sensors and flow regimes, and the discrepancy between simulated and measured results was less than ±5%.

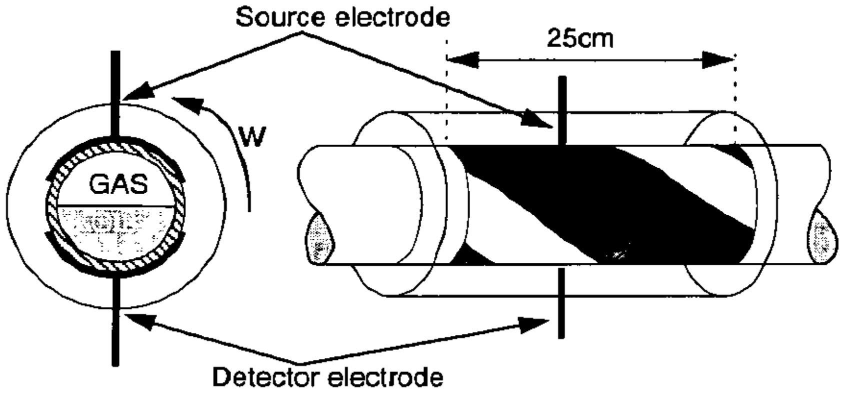

Figure 1. The 180° helical surface plate capacitance sensor configuration.

Figure 2 shows the measured and simulated capacitance characteristics for a surface plate capacitance sensor versus the angle of orientation (W) when the electrodes are straight, 90° helical, 180° helical and 360° helical. The regime consists of stratified air and glycerol at a volume fraction of 0.3.

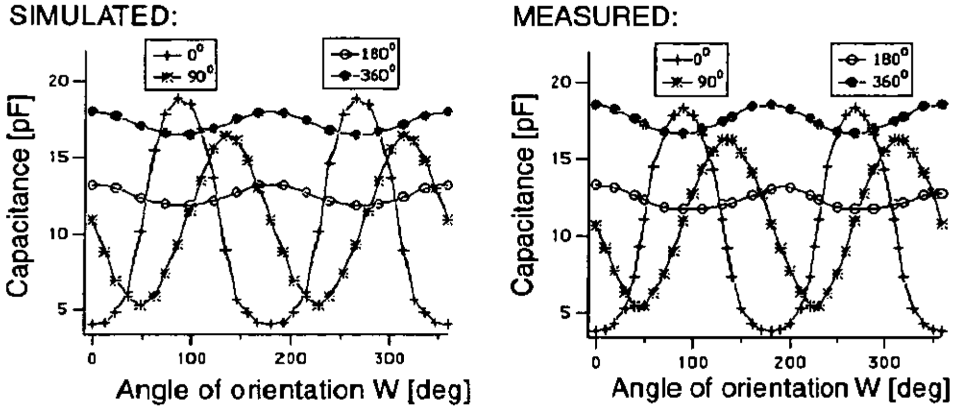

Figure 2. Measured and simulated capacitances versus the angle of orientation (W) of stratified flow for a surface plate capacitance sensor with straight electrodes (0°) and for 90°, 180° and 360° helical electrodes. The components are air and glycerol ($\varepsilon_r \approx 50$) and the glycerol volume fraction is 0.3.

Thus, by calculating the capacitance, using the 3D FEM-model, for a great number of flow regime distributions, at a fixed volume fraction, the flow regime dependency can be estimated. Figure 3 shows some of the flow regime types used in the simulations.

On basis of a large number of such randomly generated flow regimes, as those shown in Figure 3(a) to (d), the flow regime dependency has been estimated by studying the variation in the capacitance characteristics. Based on these simulations the average uncertainty in the measured oil fraction for bubble/churn/slug regimes is estimated to be about ±0.4% of full scale for the 180° helical surface plate capacitance sensor, and about ±4% for the classical surface plate capacitance sensor with straight electrodes.

Thus, the simulations indicate that using a 180° helical surface plate capacitance sensor instead of the classical sensor with straight electrodes, enables reduction of flow regime dependence by a factor of about 10 for gas and oil flows. It is, however, obvious that with annular flow the

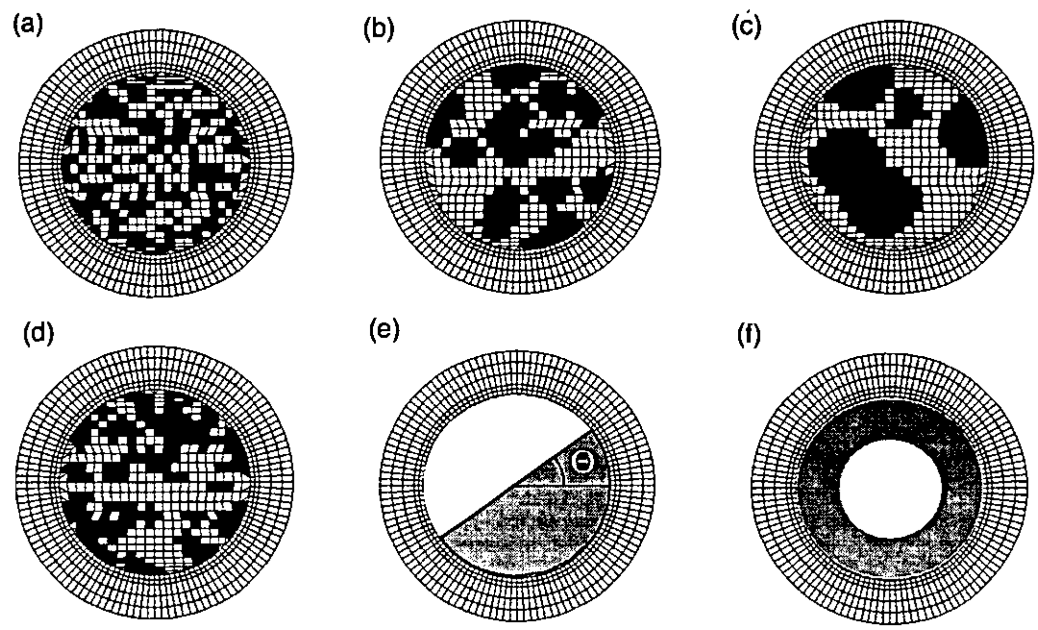

Figure 3. **a**) to **d**) Random generated bubble, churn and slug flow. **e**) Stratified flow where the angle, Θ, varies between 0^o and 90^o. **f**) Annular flow.

helical sensor and the straight electrode sensor will have the same measurement error. Finally, due to the short circuiting effect neither the helical sensor nor the straight plate sensor can be used at water continuous mixtures.

MULTI-ELECTRODE CAPACITANCE SENSORS

UMIST developed the first multi-electrode capacitance system for imaging of oil and gas in two phase flow [3]. This instrument was further developed by Schlumberger in Cambridge and used for research on two phase flow. A similar system was developed by University of Bergen/ Christian Michelsen Research AS [4]. A sketch of the basic principle of a multi-electrode capacitance system is given in Figure 4.

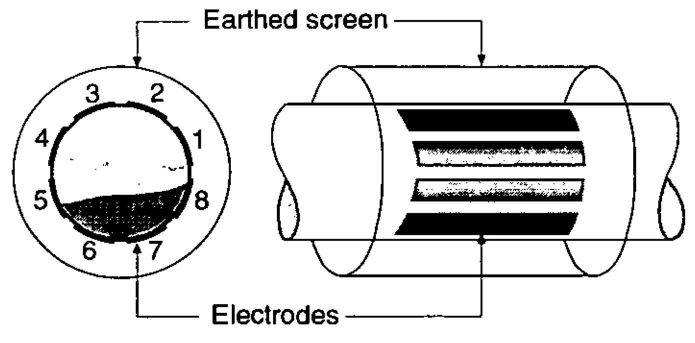

Figure 4. Basic principle of an eight-electrode capacitance sensor system for flow regime identification.

A capacitance image (tomogram) is generated by first measuring the independent capacitances between all the electrode-pair combinations. This is done by exciting the electrodes in sequence. The results of the measurements, which contain information about the dielectric constant distribution inside the pipe, are transferred by a data-acquisition system to a reconstruction unit. This converts, by reconstruction, measurement data to an image of the phase distribution across the pipe cross-section. Several capacitance multi-electrode systems using so-called modified back projection reconstruction algorithms, are in use at the multi-component flow rigs at CMR, UiB and Norsk Hydro a.s. Research Centre. Reconstructed images from the multi-phase flow rig at Norsk Hydro are shown in Figure 5.

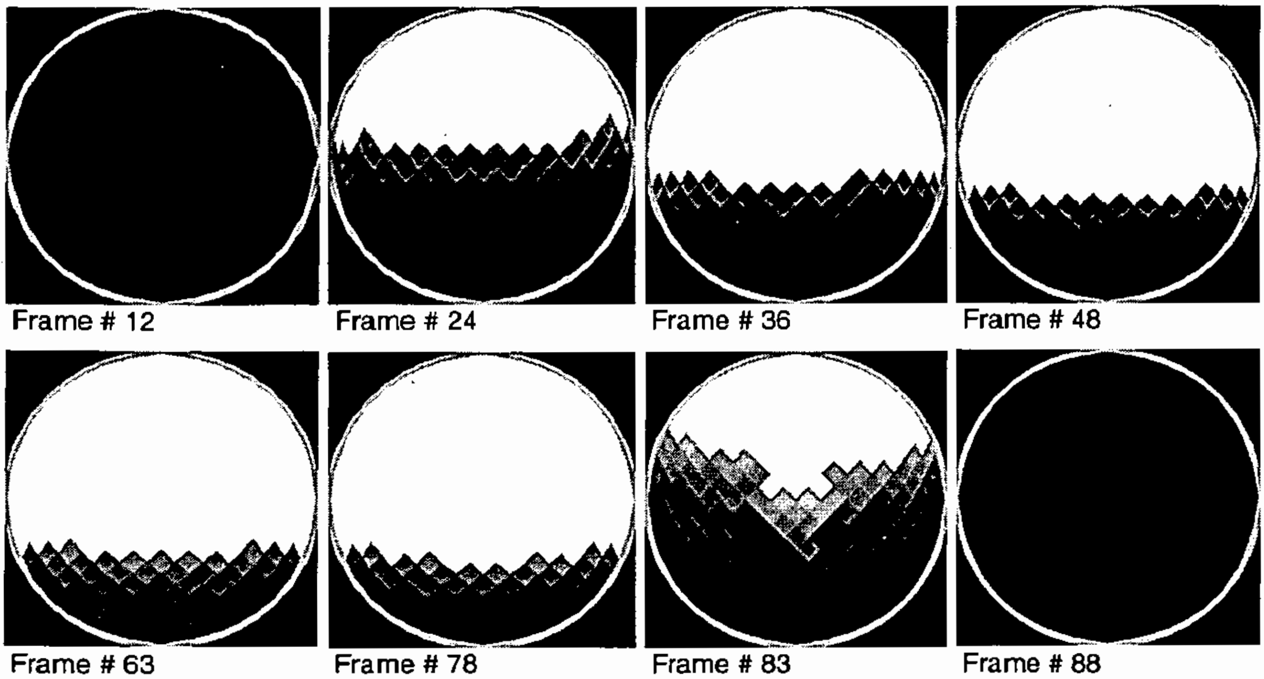

Figure 5. Oil/gas imaging with the eight-electrode capacitance tomograph and LBP-reconstruction at Norsk Hydro a.s. Research Centre [5]. The example shows the propagation of a gas bubble (slug) in horizontal flow. Note that only a few frames of the 2 seconds sequence are shown.

It is important to be aware of that the capacitance multi-electrode system can not be used directly for imaging of the component distribution in the pipe if the mixture is water continuous due to the short circuiting effect caused by the conductive water [6]. However, this effect can be utilized because it contains important information of the flow regime.

In water continuous oil/ water mixtures the electrical conductivity in the mixture will decrease with increasing oil concentration [2]. Resistance tomography based on electrodes in galvanic contact with the mixture can therefore be used to detect the distribution of the oil in the liquid. Resistance tomographs have been developed by UMIST and tested on water continuous liquids [7].

UMIST has also developed multi-electrode impedance system which are measuring both the capacitance and conductance between pairs of electrodes around the periphery of the pipe. These electrodes are uninsulated and in direct contact with the mixture. Uninsulated electrodes can be used as capacitance electrodes as well in oil continuous mixtures. Switching between capacitance and resistance measurements is well known from commercial multiphase meters (Fluenta AS).

The rotating field sensor

One example of use of the multiple capacitance electrode system is the rotating field sensor. In principle, this sensor will work as an helical sensor. Adjacent electrodes are connected together on both side of the pipe in such a way that the electrostatic field will be equal to an ordinary surface plate sensor. By adding one electrode at a time at one side and delete one electrode at the other side of each electrode "plates" the field will rotate and the mean value of one rotation is calculated: The result of this is shown in Figure 6

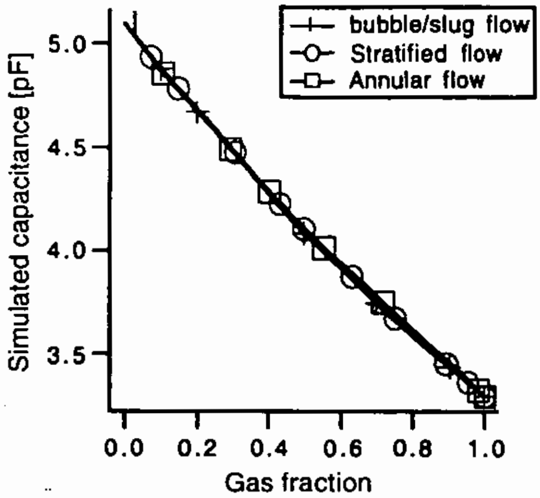

Figure 6. Measured capacitance as function of gas fraction in oil for a 16-electrode rotating field sensor. The mean capacitance is calculated using the finite element models for the electrostatic field distribution at the different regimes shown in figure 3.

The accuracy of this system is calculated to be ± 0.5% of the total range for all the different regimes shown in Figure 3, i.e. a performance comparable to that of the helical electrode sensor.

Rotating field is a simple way of utilizing the information available from multi-electrode sensors. By taking measurement between all possible combinations of the different electrode segments, like in imaging systems, a much more flow regime independent detection can be done.

MULTIPLE BEAM GAMMA-RAY DENSITOMETRY

Gamma-ray densitometry is a frequently applied method for measuring density or component fractions of multi-component flows. A gamma-ray densitometer typically uses a shielded and collimated nuclear isotope on one side of the pipe cross section and a radiation detector system operated in pulse counting mode on the other side (see figure 7). The read-out system consists of an amplifier and filter circuitry where the output pulse amplitude is proportional to the detected radiation energy. The average density, or more correct, the average linear attenuation coefficient of the flow is found by counting the number of transmitted photons in a certain energy window over a period (the integration time). In single energy densitometry this energy window normally covers only the full-energy peak of the desired emission line of the isotope, whereas in multiple energy densitometry several windows and counting circuits are used to cover the emission lines of interest.

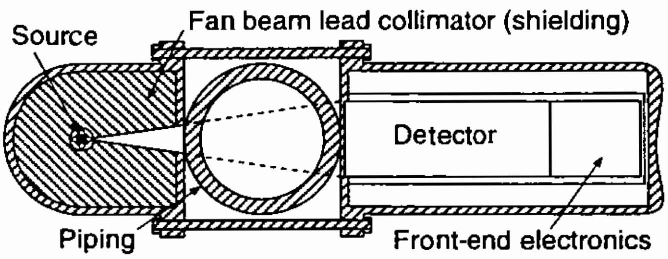

Figure 7. Schematic view of a typical clamp-on gamma-ray densitometer.

Measurements with this type of single beam gamma-ray densitometers are flow regime dependent since the flow cross-section normally is only partially covered by the measurement volume (see figure 7). To cope with this, compensations are made to reduce the measurement error. These compensations are either based on measurements from other meters, models assuming the flow regime is known, or a combination of these.

The flow regime dependency can be reduced, and practically removed, by utilising a multiple beam system. The feasibility of such a system is demonstrated by a gamma-ray flow imaging tomograph developed by the University of Bergen (UoB) [4]. This instrument uses five radiation sources and 85 compact detectors in an arrangement schematically shown in figure 8. Experiments show that it is possible to do three-component flow regime identification and void fraction measurements at rates several of hundred frames per second with this system, provided the reconstruction unit has sufficient computing power [8].

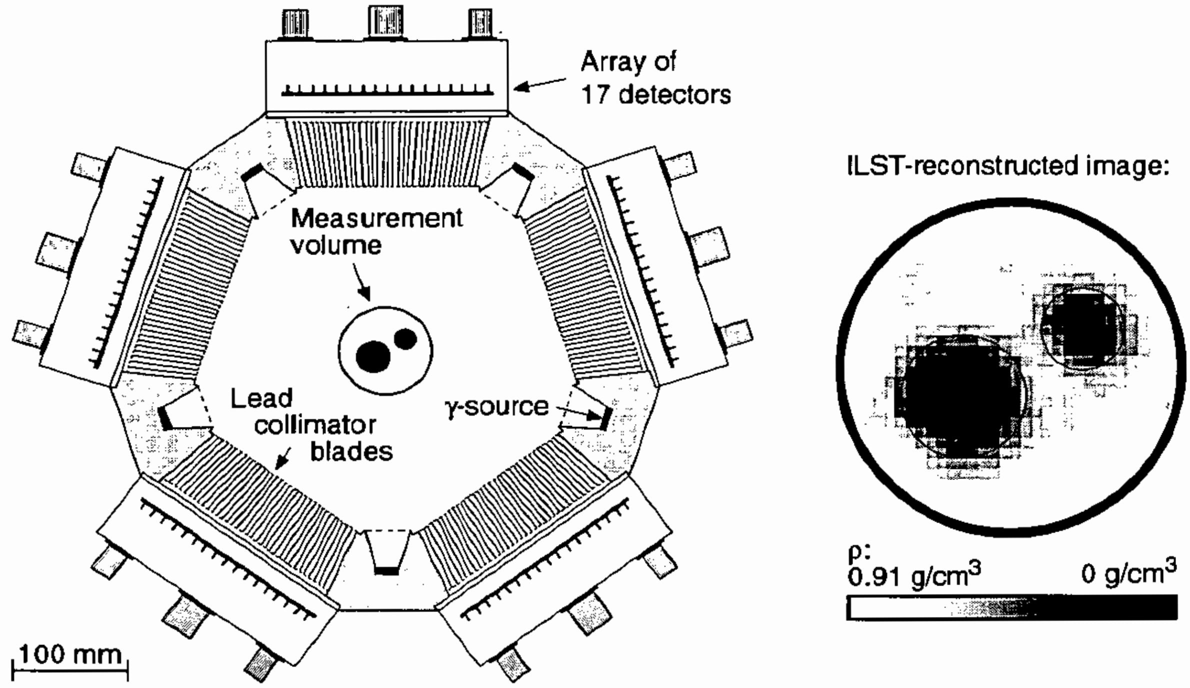

Figure 8. Cross sectional schematic view of the 85-channel UoB gamma-ray tomograph with a reconstructed image of a gas/liquid phantom (where the circles show the true surface position of the gas bubbles).

It should be emphasized that this tomograph is meant for research purposes only, and not as a part of a multiphase meter. It is, however, possible to reduce the number of radiation sources and detectors in comparison to the tomograph, and still be able to identify the flow regime and calculate the void fraction. A system using one source and three detectors embedded in the pipe wall is now being developed and characterized, see figure 9. In order to fully utilize the

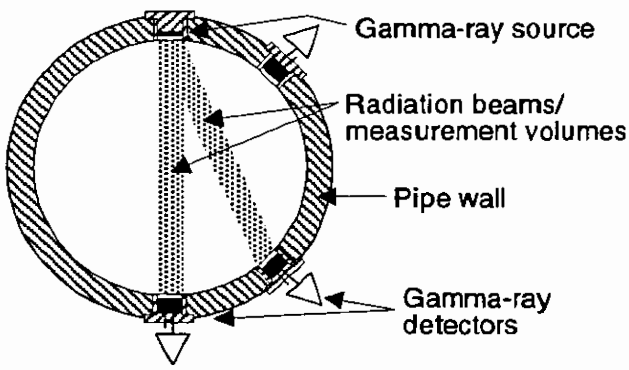

Figure 9. Cross sectional illustration of a multiple beam gamma-ray densitometer using one radiation source.

measurement principle this measures scattered radiation in addition to the transmitted radiation. An experimentally verified simulation model (EGS4) of this densitometer has been developed and used for homogenous, stratified and annular flows. Results with this model show distinct differences in the spectral responses of the detectors for the different flow regimes. These data may therefore be used to identify the flow regime in addition to measuring the void fraction.

Neural networks have been used successfully in the interpretation of simulated data from this multiple beam densitometer. Both flow regime and void fraction were accurately determined for relatively simple flow regimes. One attractive feature of combining neural networks and system models, is that the model can be used to generate training data for the network at different conditions. This, which of course requires accurate (and verified) models, simplifies the use of neural networks which otherwise could be too complex to utilise.

Gamma-ray measurement which are frequently used in other down-hole applications, e.g. lithology and neutron density logging, is known to be a reliable and relatively inexpensive technique. There are several possibilities when it comes to the realization of a multi-beam gamma-ray densitometer: Concerning geometry, several measurement planes (sets of densitometers) may be required, eventually with different radiation energies to allow three component fraction measurements. The integration of source(s) and detectors in the pipe wall is necessary to achieve the desired compactness. This, in turn, calls for compact radiation detectors. One solution may be novel semiconductor detectors where the latest developments have led to substantial improvements in performance and reliability [9, 10]. Dense semiconductor detectors fulfils the efficiency requirement provided low energy sources such as 241-Am (60 keV) are used. This is feasible here since the high penetration capability of clamp-on meters using high energy sources like 137-Cs, is not required. Lower energy is also advantageous from a safety point of view, since the radiated dose from a low energy system is several orders of magnitude less, even with less shielding and higher intensity. The latter is desirable as it is the key to improve measurement accuracy [11].

MULTI-SENSOR SYSTEMS IN MULTIPHASE FLOW METERING

The multi-sensor principle can be used in two different ways to improve the multiphase flow metering:

- By detecting the flow regime in the measurement volume.
- As a multiphase flowmeter

The first method is based upon the fact that if the flow regime is known the measurement results from different sensors used in the multi-phase flowmeter can be corrected according to their flow regime dependency. The second method is much more elaborated and represents new possibilities in multiphase flow metering.

It is necessary to have two independent measurements of the mixture characteristic parameters to determine the fraction of each component in a three component mixture. The two measurements makes two independent equation and the third equation is simply the sum of all fraction in the measurement volume which is equal to one.

For fraction measurement in an oil/water/gas mixture common independent measurements are density and electric permittivity. The density is mainly sensitive to the gas fraction and the permittivity is mainly sensitive to the water fraction in the mixture. Density is usually measured by a one beam gamma-ray densitometer and the permittivity is measured either by two electrode capacitance sensors or by microwave sensors. If the permittivity measurement can be done by a capacitance or microwave multi-sensor system, the permittivity distribution in the meter cross section, and hence the flow regime, will be known. Thus the gamma-ray measurement can be corrected for flow regime dependent error.

A multiple beam gamma-ray densitometer can be utilized in the same way to make the two-electrode permittivity detector flow regime independent. Some meters are using two energy gamma measurements. This principle is based upon the fact that the attenuation of gamma photons is dependent on the gamma source energy. Using two different gamma-ray energy sources two independent measurements can be done. A single energy gamma-ray densitometer with multiple beams together with a one-beam gamma densitometer using a different energy, can make the instrument flow regime independent and hence the in line mixer can be omitted.

Here, capacitance, resistance and the gamma-ray sensor principles have been discussed, but other sensor principles like microwave-, inductance- and to some extent ultrasound-techniques, can be applied in multi-sensor mode to make the system less flow regime dependent [12].

Down hole multiphase metering

The existing multiphase meters have already been taken into use sub sea, but only for process measurements. There is a demand for using the sub sea multiphase meters for allocation purposes but that can only be done if these meters obtain an increased accuracy. This accuracy will be dependent on the economical balance; i.e. the reduction of installation costs by using sub sea meters in stead of top side separation. It is likely to believe that if the multiphase meters can display an accuracy of ±5% of measured flow rate, these meters will be of great economical interest for the oil production companies.

The necessity of accuracy will be less if the multiphase meters are used only for process optimization or control purposes like in down hole metering. Nevertheless, since the production pipes in a well often are positioned inclined and horizontal the flow regime will be so different from homogeneous mixed regime that it will be necessary to use multiple sensors for multiphase metering. Modern drilling technology has also made it possible to drill lateral wells connected to a common production pipe (see Figure 10).

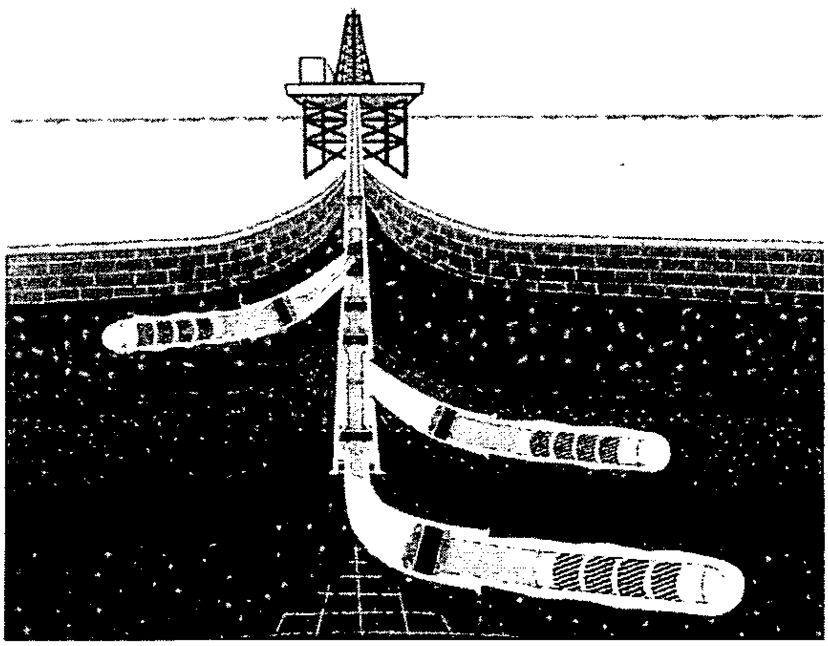

Figure 10. Example of a three-lateral well. Booker Field, Malaysia [13].

The lateral production pipes are either positioned inclined or even horizontal, and the flow regime in these pipes are unpredictable. It is vital for efficient production to measure the content of the flow in each production pipe. Thus the production can be optimized. (A lateral well that produces mainly water can be shut off; or by reposition the flowmeter, zones producing too much water can be plugged).

The only known technique that can be used for measuring the flow of the different components in the flow regimes, likely to occur in these type of wells, is actually the multi-electrode technique.

A down hole meter must be able to work at high pressure (up to 300 bar), and high temperature (up to 200 °C) and limited space. This, and the requirement of multiple read-out channels, make it necessary to apply micro electronics to obtain the desired compactness and reliability. The maximum temperature for conventional electronic circuits is presently 150^{0}C. At higher temperatures the current leak will increase rapidly. Ongoing research on High Temperature Application Specified Integrated Circuits (HTASIC) [14] has shown that those special designed circuits can operate, and will have an acceptable long-term stability, at temperatures up to 220^{0}C.

This indicates that multi-sensor, multiphase flowmeters can be designed to be used down hole. Capacitance- and resistance electrodes are the less space consuming detectors. An impedance multi-sensor system containing two independent measurements; capacitance and resistance. It might be possible, by using high-frequency detector circuits to develop multiphase flow regime independent meters with the desired accuracy for down hole metering. and a system based on this dual detection will probably give the demanded accuracy for a wide range of component ratios by utilizing the additional spatial information a proper multi-electrode system will give.

CONCLUSON

The latest developments in multi-sensor systems and high temperature micro electronics can be utilized to develop flow regime independent multiphase flowmeters which can be used down hole. Even helical capacitance or conductance electrodes used together with the multiple gamma ray densitometer, using one radiation source, may be utilized in a down hole meter with acceptable accuracy for down whole multiphase metering.

The research and development done so far, within this subject, indicates that the necessary reliability and accuracy can be obtained. The necessary technology is available but the question is: Will the cost of development pay off?

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