A FLOW-REGIME INDEPENDENT MULTIPHASE FLOWRATE METER

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SUMMARY:

In a paper presented at the North Sea Flow Measurement Workshop in 1990, Christian Michelsen Research (CMR) presented test results for a new concept for measuring the phase fractions of a multiphase flow. In the follow-up of this work, a new project to develop a multiphase <u>flowrate</u> meter was initiated in June 1990. This has now resulted in a commercially available multiphase meter, the Fluenta MPFM 1900.

The new flowrate meter is of a non-intrusive design, and mounted in a vertical upwards flow, it will accept a wide range of flowrates and compositions without any preconditioning of the flow. This has been achieved by advanced signal processing, and by building knowledge of multiphase flow behaviour into the model based measurement system. The distribution of velocities present in the flow are measured by correlation techniques, and thus interphasial slip is directly measured and compensated for.

The paper discusses why installation of mixers for preconditioning of the multiphase flow should be avoided, and it presents test results from extensive laboratory testing of the new multiphase flowrate meter. The first field test installation is already in progress.

THE FLUENTA MPFM 1900;
A NEW MULTIPHASE FLOWRATE METER DEVELOPED BY CHRISTIAN MICHELSEN RESEARCH

In a paper presented at the North Sea Flow Measurement Workshop in 1990 [1], Christian Michelsen Research (CMR) presented test results for a new concept for measuring the phase fractions of a well mixed multiphase flow. The measurement principle is shown in Figure 1: Based on the density of a well mixed multiphase flow as measured by a clamp-on gamma densitometer, and the permittivity of the same flow as measured by a non-intrusive in-line capacitance sensor, the fractions of oil, gas and water at the sensor location are determined. This principle of measurement has been realised in the Fluenta MPFM 900 Multiphase Fraction meter.

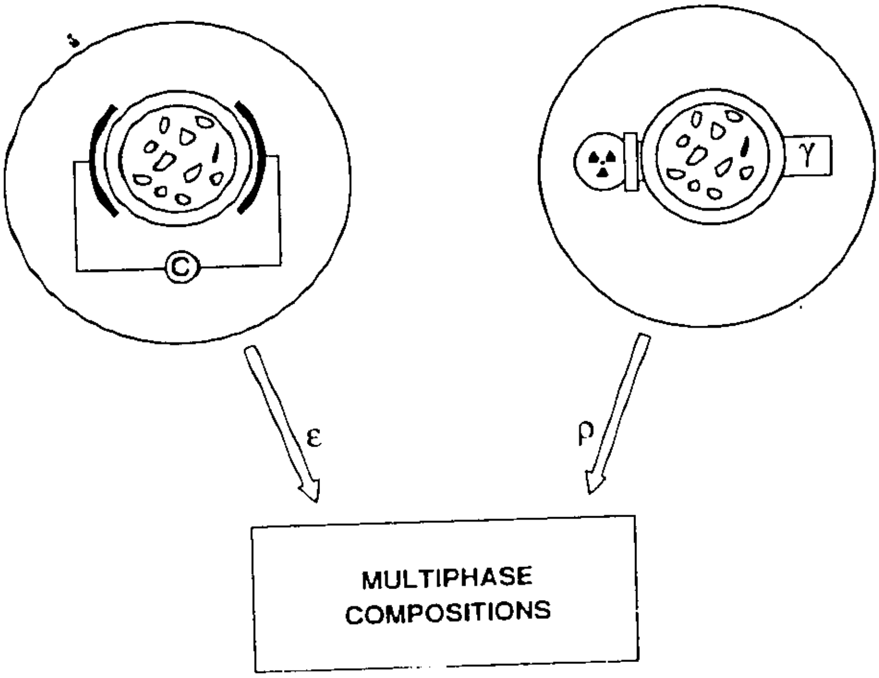

Figure 1 Measurement principle of the MPFM 900.

With support from BP Norway, Saga Petroleum, Elf Petroleum Norge and the Norwegian Petroleum Directorate, we have now also developed a velocity measurement technique based on cross correlation of signals from a multi-electrode capacitance sensor. Assuming that there is no inter-phasial velocity slip between oil, water and gas, this velocity measurement can be combined with the MPFM 900 in order to provide a multiphase flowrate meter suitable for no-slip conditions.

However, tests early in this project indicated that interphasial slip between liquid and gas is significant in a vertical multiphase flow, and is re-established rapidly after a mixing point. At best, no-slip will be established only over a limited range of flow rates and compositions, thereby limiting the range of any no-slip measurement system.

Therefore, the electrode layout and detector system of the capacitance sensor was optimised in order to be able to discriminate between the velocity of small bubbles dispersed in the liquid, and the velocity of fast moving larger bubbles/slugs. By using this additional information, in combination with knowledge of multiphase flow behaviour, the model based measurement system directly determines, and accounts for, interphasial slip. The new flowrate measurement system does therefore not require any upstream mixer to be installed.

The performance of the complete measurement system was put to a thorough test in the CMR multiphase flow-loop during March '92. The results from these performance tests are very satisfactory. Over most of the tested range, measured flowrates of liquid and gas are found to be well within ±5% from the reference flowrate.

As part of the test programme, two "production profiles" during approximately 3 hours were produced through the multiphase flowrate meter, and accumulated volumes of oil, gas and water were measured. During such a test all random errors due to natural fluctuations in the flow are filtered out and become insignificant, and the effects of any systematic errors are clearly shown. In Figure 2 it is shown how the liquid flow rate during one such test period has been varied between 35 and 45 m3/h, while gas flow rate has been varied between 10 and 35 m3/h. The water cut has been varied in the range 15-22 %. The results of this "production test", which could be compared to a test-separator run, are shown in Figure 3 and Figure 4.

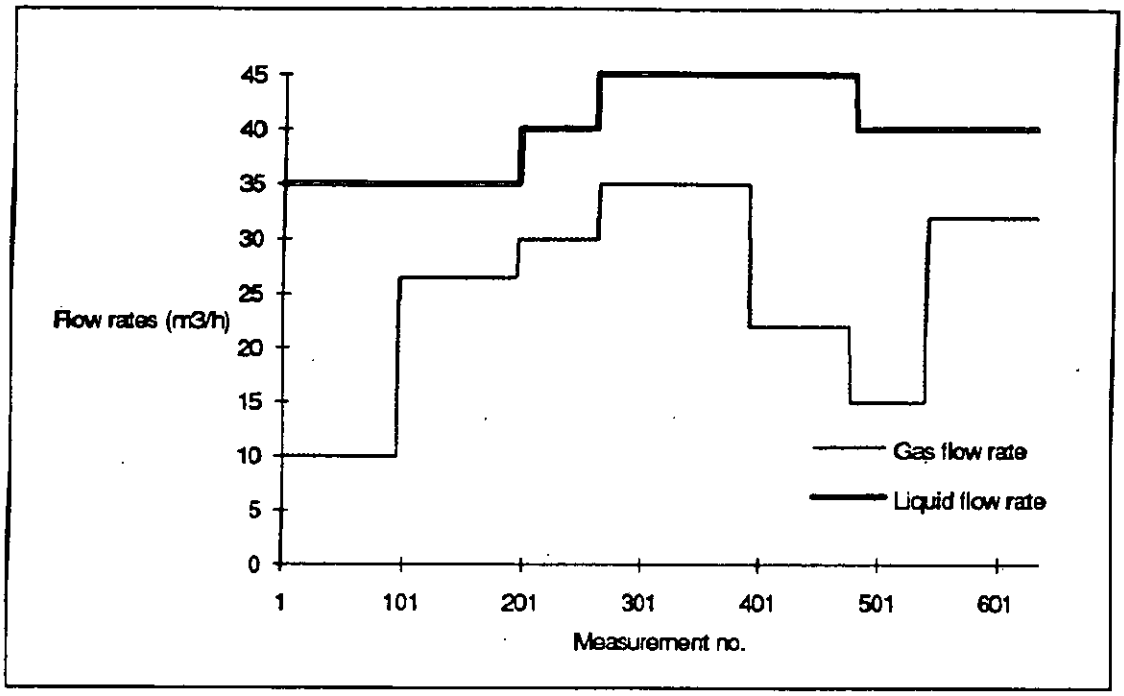

Figure 2 Production test. Production profiles of liquid and gas.

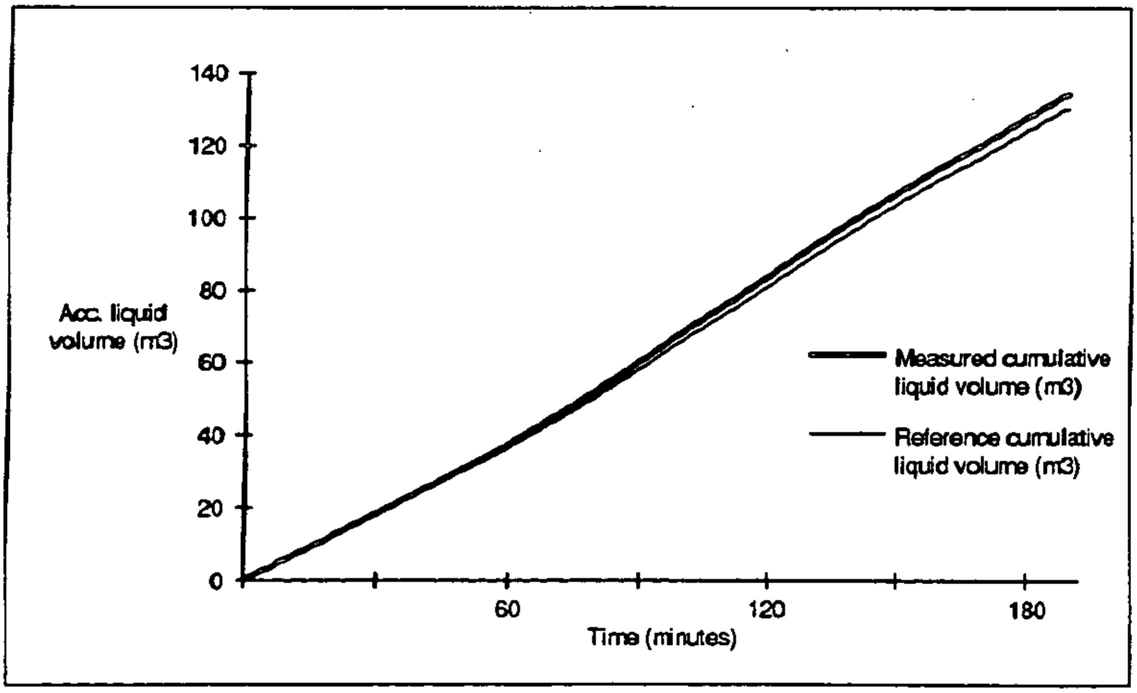

Figure 3 Measured accumulated liquid volume during a production test.

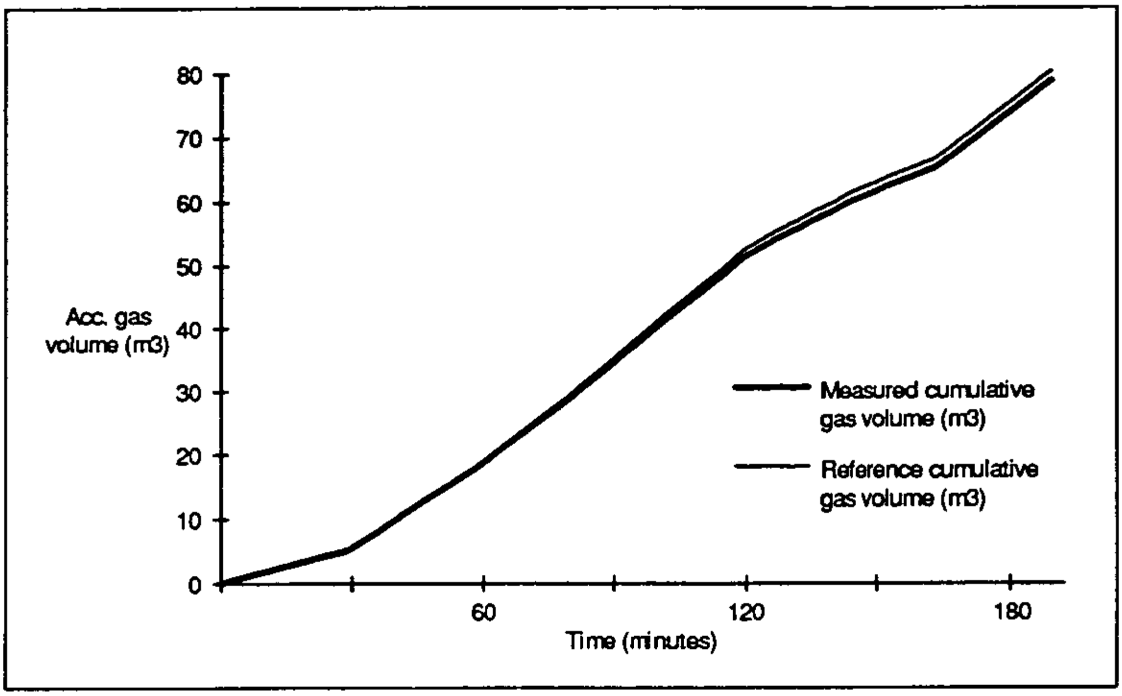

Figure 4 Measured accumulated gas volume during a production test.

The discrepancies between measured and reference volumes of liquid and gas in the two production tests were found to be between 2% and 5.5%. During the period of these tests the corresponding water-cuts were measured to be 14.7% and 19.7%, as compared to reference values of 13.0% and 19.4%, respectively.

Based on these very encouraging test results, Fluenta has already made an industrial version of the meter available to the market. This has been made possible through the co-operation with Conoco and the Norwegian Research council (NTNF) within the KAPOF - programme.

In the new instrument, analogue signals are converted to digital at the sensor head, and all signal transmission between the sensor and the control room unit is in digital form on a fibre-optic link. Thereby a low power, but high speed signal transmission has been achieved. The sensor head has also been fitted with a pressure compensation system. With this design the maximum pressure is no longer limited to the ceramic liner specifications. The measurement system has been approved by Baseefa for use in hazardous areas. Also the user interface has been improved from the MPFM 900 version.

The new meter, The MPFM 1900 Multiphase Flowrate meter, replaces the MPFM 900 fraction meter on the market. Saga Petroleum has purchased the very first unit, and following a successful factory acceptance test in the CMR laboratory in August '92, Saga is now (September '92) in the process of installing the meter at Gullfaks B for offshore field testing.

The results of the performance testing of this new flowrate meter, prior to the delivery to Saga, are presented later in this paper.

NON-INTRUSIVE MEASUREMENT OF THE FLOWRATES OF OIL, WATER AND GAS IN A NON-CONDITIONED MULTIPHASE FLOW IS A COMPLEX MEASUREMENT PROBLEM

A variety of different flow patterns must be expected to occur in a non-conditioned multiphase flow. By restricting installation of the multiphase meter to vertical upwards flow, the possible flow patterns are fewer, usually classified into four flow regimes exhibiting significantly different features (see Figure 5):

In *bubble flow* the gas is uniformly distributed as small gas bubbles dispersed in a continuous liquid phase. It generally occurs when the gas flowrate is low compared to the liquid flowrate.

The *slug flow* regime develops from a bubbly pattern when the gas flow rate increases to such an extent that it forces the dispersed bubbles to become closely packed and coalesce into larger gas volumes. Stable slug flow is generated at high gas rates in pipes of long free vertical stretches.

Churn flow is observed as a transition regime from bubble to slug flow, and may also be experienced at very high gas flowrates in the transition region from slug to annular flow.

In *annular flow* the liquid phase moves upwards partly as a wavy liquid film along the pipe wall, and partly in the form of small droplets entrained in the gas core. Annular flow occurs when the flowrate of gas is significantly higher than that of the liquid.

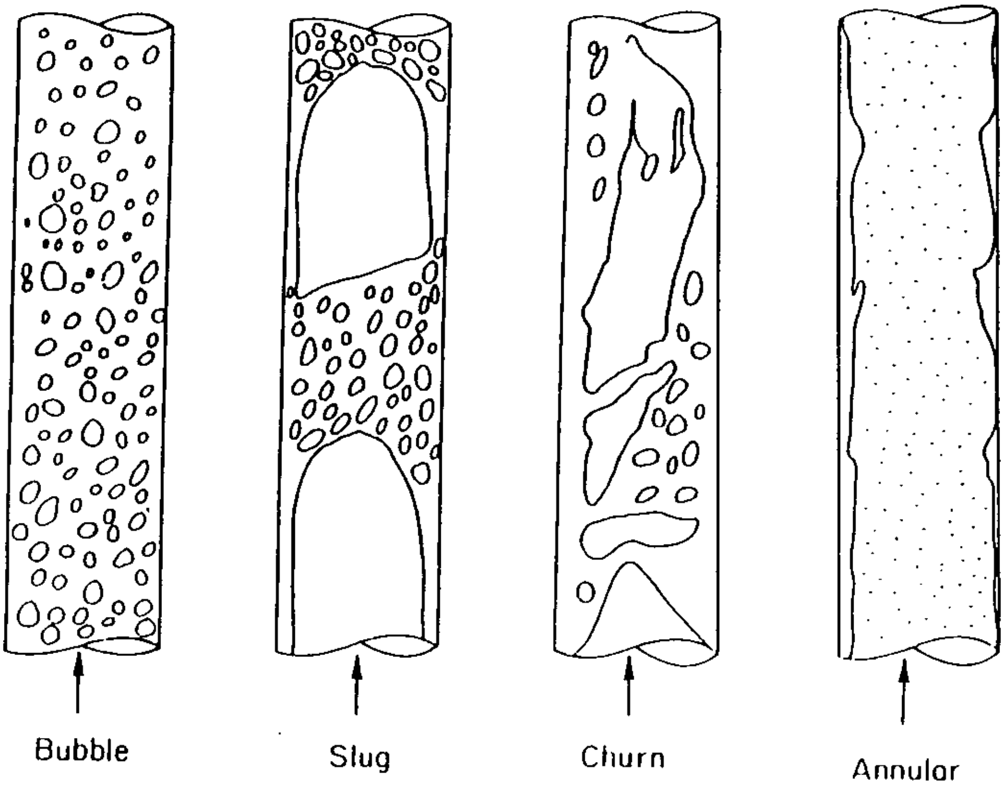

Figure 5 Flow patterns in vertical flow.

The natural grouping of gas and liquid into specific flow regimes at different flow conditions, clearly means that one cannot assume the gas to be uniformly distributed in the liquid across the cross-sectional area of the pipe. The degree of in-homogeneity will increase at high gas flow rates. The gas is only uniformly distributed in the liquid in bubble flow. For all other regimes the gas tends to collect itself in the middle of the pipe as large bubbles in slug and churn flow, and even more dominant in the form of a gas core in annular flow.

In a gas-liquid flow, the larger bubbles will rise in the fast moving liquid in the centre of the tube, other small bubbles will be near the wall and will consequently move more slowly. This velocity slip is further enhanced by buoyancy due to the difference in density of gas and liquid so that the gas phase will be transported with a larger average velocity than the liquid phase.

To measure multiphase flowrates in a non-conditioned multiphase flow, it is therefore necessary both to measure the total velocity distribution of the flow, as well as to measure and account for any in homogeneous phase distribution at the sensor location.

WHY NOT REDUCE THE COMPLEXITY OF THE MEASUREMENT PROBLEM BY PRECONDITIONING OF THE MULTIPHASE FLOW?

Within a certain range of multiphase compositions and flowrates, an inline mixer may be employed in order to reduce the interphasial slip to a minimum, and in order to create a radially homogeneous phase distribution, at the location of the multiphase meter. The efficiency of a mixer to achieve this, as well as the range over which sufficient mixing is achieved, and to which cost in terms of pressure drop, will to a large extent depend on the different mixer designs.

There are a range of different mixers available, both inline static devices which draw the mixing energy from the flow itself, as well as dynamic mixers which require energy input. One advantage of using some type of dynamic mixer is that little or no pressure drop is created across the mixer. However, in most cases a static mixer will be preferred, because no energy input is required, and because they generally are rugged devices with no moving parts. Pressure drop across a static mixer will typically be in the order of 0.5 to 3 bar, depending on flowrate and composition.

A multiphase flowrate meter which depend on a mixer to provide suitable measurement conditions will lend itself to the efficiency of available mixers. The range of such a flowmeter will be limited by the range where sufficient degree of mixing can be guaranteed. The uncertainty with respect to remaining slip at the flowmeter location, and/or in homogeneity of the radial phase distribution, will add a significant contribution to the overall measurement uncertainty.

To our knowledge a thorough analysis of the performance of mixers for use with multiphase meters has never been performed. It is however evident that even the most efficient mixer will not be able to create no-slip conditions and homogeneous phase distribution over an un-limited range of flowrates and compositions. Since the overall performance of many multiphase meters will directly depend on the performance of available mixers, a comprehensive test program for evaluation of available mixers over a wide range of flowrates and compositions should therefore be initiated. Some parameters important for evaluation of the mixer performance in such a test programme will be bubble size distribution, velocity profile, interphasial slip, axial and radial phase distribution, and pressure drop.

Awaiting the results of such a test programme, and, until now, not having identified a mixer with suitable performance parameters, we at CMR have chosen to accept the existence of slip, and to develop methods to measure the degree of interphasial slip, rather than try to avoid it by mixing.

In addition, we believe that the industry will see some advantages with a completely non-intrusive system with no pressure drop. In particular, some multiphase pipelines even require pressure boosting in order to transport the flow from a remote satellite to a processing platform. Since increasing the line pressure just a few bar using a multiphase pump will be quite expensive, it does not appear very cost efficient to consume pressure head just for the sake of creating suitable measurement conditions for a multiphase meter.

The major drawbacks by having to rely on a multiphase mixer can therefore be summarised as follows:

- it is not evident that there exist a multiphase mixer which will be able to create no-slip conditions and homogeneous phase distribution over a sufficiently large range of flowrates and compositions
- the range of the multiphase meter will be limited to the range where a mixer is able to provide acceptable flow conditions
- any remaining slip, or in-homogeneous phase distribution, will directly contribute to the overall measurement uncertainty
- the pressure drop can be significant

MEASUREMENT OF MULTIPHASE FLOWRATES UNDER PHASE SLIP CONDITIONS

As previously described, the gas in an un-conditioned vertical multiphase flow will be transported with different velocities relative to the bulk average velocity, depending on flow regime and bubble sizes. While small bubbles dispersed in the liquid phase will be transported with close to no slip, larger bubbles or gas slugs will take on a slip velocity in the range from 0.5 to 2 m/s relative to the liquid velocity. Therefore, in principle, the total velocity range must be measured, and correct volume fractions of liquid and gas must be allocated to each part of the velocity range. In order to do this correctly, we have found it necessary to try to understand the behaviour of multiphase flow, and to build such knowledge into signal interpretation models in the model-based measurement system.

Schematically the new multiphase flowrate meter is illustrated in Figure 6. Its operation will be described in the following.

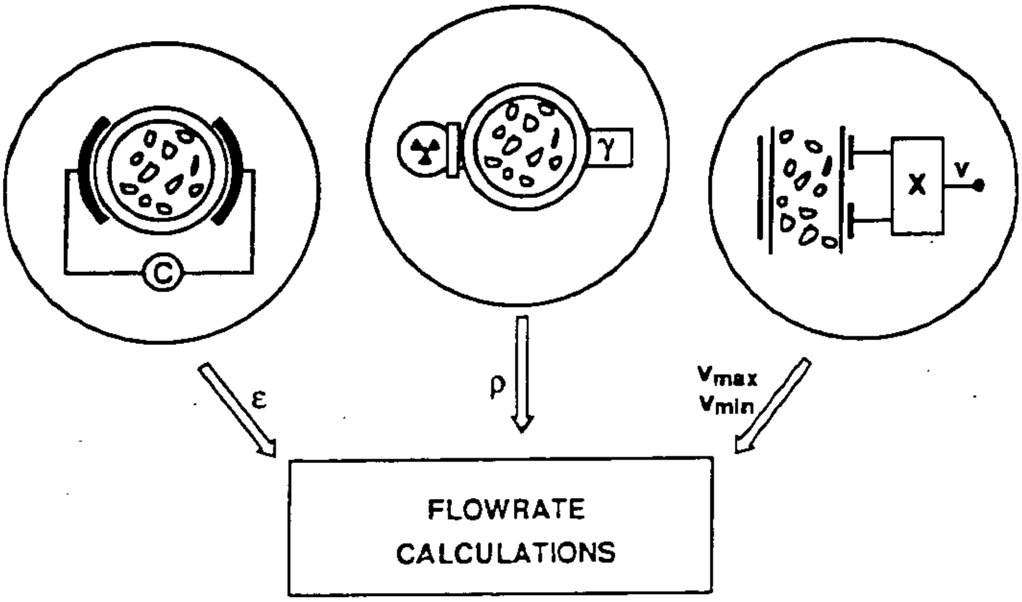

Figure 6 Measurement principle of the CMR multiphase flowrate meter.

Measurement of phase fractions

As in the MPFM 900, the multiphase fraction routine is based on a non-intrusive capacitance measurement to determine the mean permittivity (dielectric constant) of the mixture and a gamma meter measurement to determine the mean density. From these two independent measurements, and knowing that the sum of all the fractions will always be equal to one, the individual fractions of oil, gas and water at the sensor location are determined. Laboratory tests have shown that this measurement system is capable of determining the composition of a multiphase flow to an uncertainty of better than ±3% for each of the components [1]. The tests have been carried out in a vertical upwards bubble/churn flow in a gas fraction range from zero up to about 60%. A larger uncertainty is experienced at higher gas fractions where the impact from the in-homogeneous phase distribution becomes more significant as previously explained.

Measurement of phase velocities

The phase velocities are determined using cross-correlation of signals provided by different sequentially located surface plate capacitance electrodes. The gas phase in a multiphase flow generally comprises several velocity components.

Different sensor geometries or electrode lay-outs have shown to be sensitive to different bubble sizes of the flow due to different spatial averaging of the variations detected. It is also possible to use different types of detectors being sensitive to different physical properties of the mixture. In addition, further pre-conditioning of the signals may be carried out as they are recorded as discrete time series. This further tuning of each specific technique includes determination of optimal values of parameters connected to the correlation computation such as logging frequency, number of samples in time series, filtering schemes and averaging methods.

During the project correlation methods have been developed which determine two significant flow velocities of the flow. These are the velocity of the fast moving larger gas bubbles/slugs, and the velocity of the small bubbles dispersed in the liquid (with velocity very close to the liquid velocity). Slip between water and oil is generally assumed very low for crude oils in a vertical upward section, and is therefore neglected in the models.

Interpretation based process model for determination of the individual flowrates of oil, gas and water

To achieve the overall objective of obtaining the individual component flowrates of oil, gas and water, the velocities must be correctly combined with measured cross-sectional area proportions of the three phases. Since the gas phase moves with different velocities, the fraction routine has been further developed so that in addition to the average gas fraction, the fraction of large gas bubbles, as well as the fraction of small gas bubbles dispersed in the liquid, are measured online [2].

The signal interpretation models use these fractions, and the two significant flow velocities, to calculate the volumetric flow rates under phase-slip conditions. The interpretation based model thus determines the total gas flowrate as the sum of gas transported as large bubbles/slugs (Q_{GB}), and gas transported as small bubbles uniformly distributed in the liquid phase (Q_{GD}):

$$Q_{GAS} = Q_{GD} + Q_{GB}$$

The mutual order of magnitude of Q_{GD} and Q_{GB} will vary depending on the actual flow regime appearing in the flow.

In bubble flow the gas is mainly transported as small dispersed gas bubbles. In such a condition the main contribution to the gas flowrate is from Q_{GD}.

In churn flow there are larger bubbles moving faster than the surrounding highly aerated liquid mixture. In such flow conditions there is also a volumetric contribution, Q_{GB}, from the faster moving churn bubbles along with the flowrate provided by small dispersed gas bubbles in the liquid, Q_{GD}.

In slug flow, an even larger portion of the gas will be carried by the large bubbles compared to the condition of churn flow.

RESULTS FROM LABORATORY TESTS OF THE MPFM 1900

During August 1992, prior to delivery to Saga Petroleum, the performance of the new MPFM 1900 Multiphase Flowrate Meter was put to a thorough test in the CMR multiphase flow-loop using diesel oil. The test programme included a wide range of flowrates and compositions.

Some volumetric flowrate results of the performance tests are shown in Figure 7 and Figure 8. Each point in the plots is the average of 10 independent measurements. The flow condition in the vertical test section of the CMR loop was bubble and churn flow.

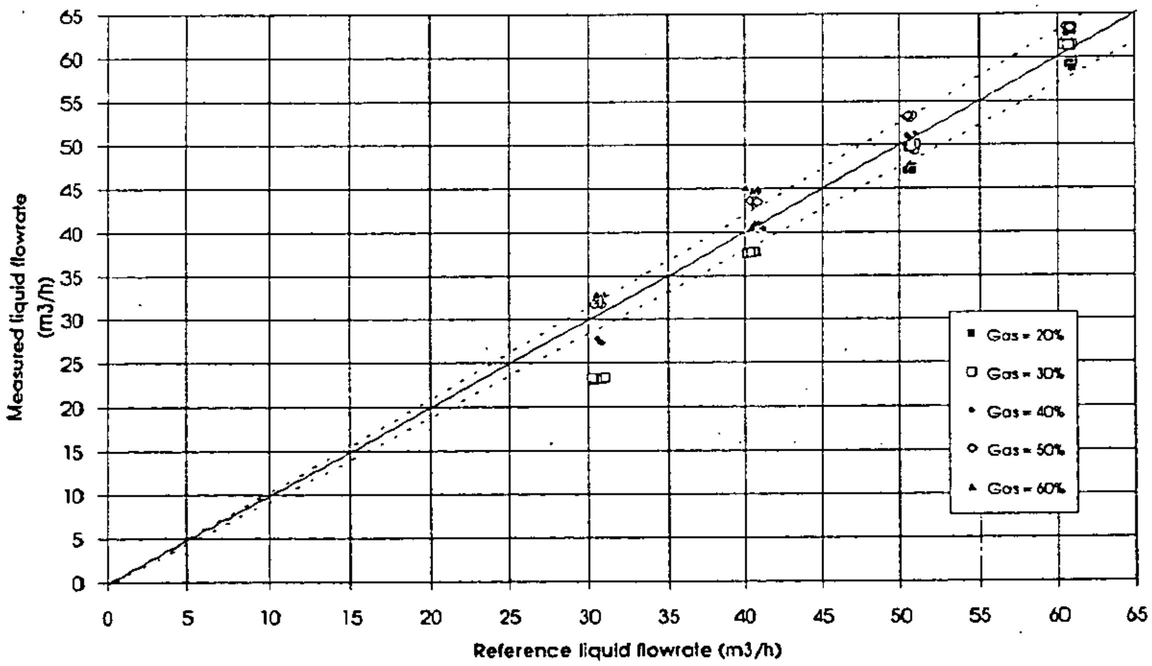

Figure 7 Liquid flowrate test results (m^3/h). Nominal gas fractions: 20-60%. Water cut 20%. The dotted lines represent the ±5% relative error.

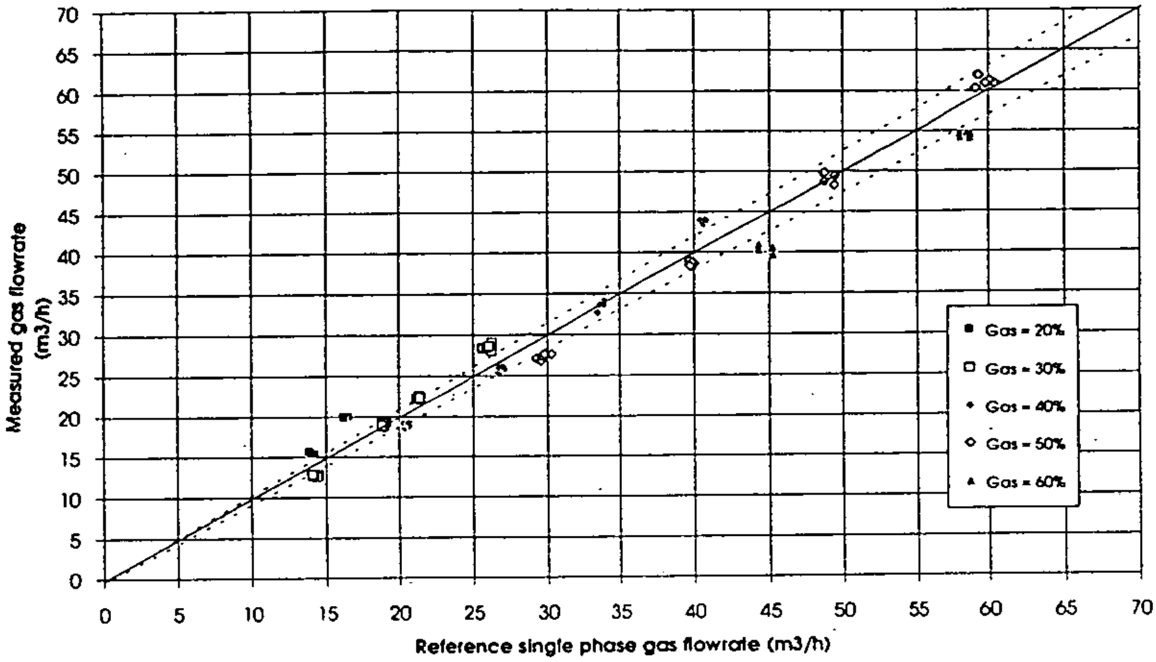

Figure 8 Gas flowrate test results (m^3/h). Nominal gas fractions: 20-60%. Water cut 20%. The dotted lines represent the ±5% relative error.

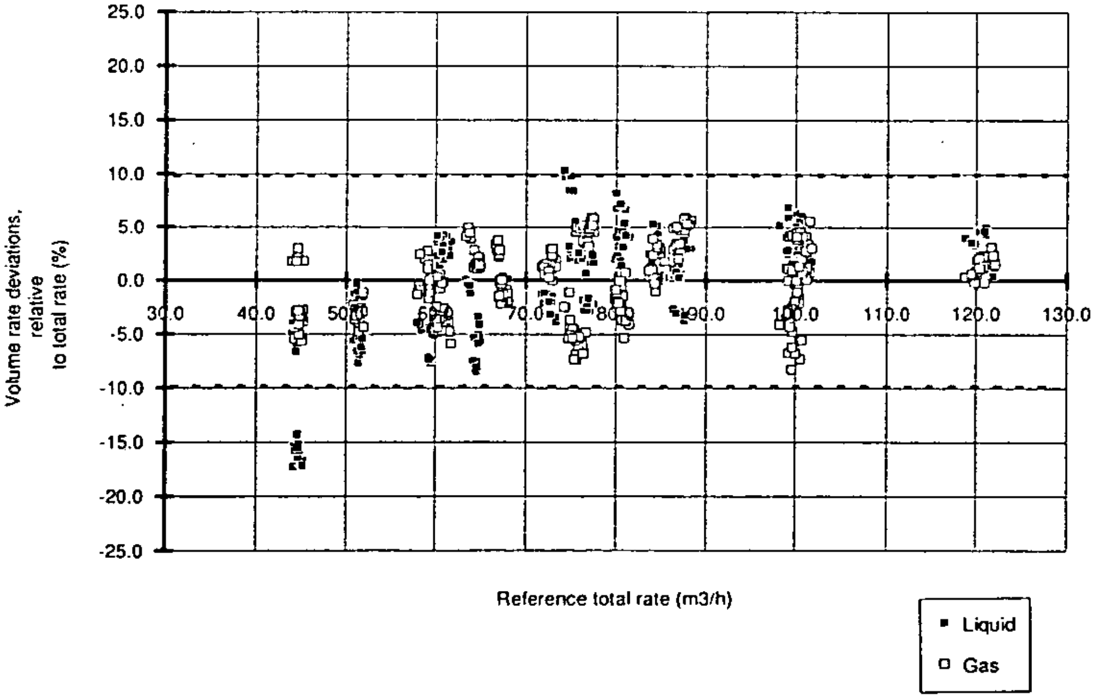

Figure 9 Deviations between measured and reference gas and liquid flowrates, relative to actual total flowrate. Nominal gas fractions: 20-60%. Water cut 5 - 40%.

The results from these performance tests are very satisfactory. Generally, over most of the tested range, measured flowrates of liquid and gas are found to be well within ±10% from reference single phase flowrates at the rig. Over a somewhat reduced range, the agreement between measured flowrates and reference flowrates is within ±5%. As we can see from the flowrate deviation plot in Figure 9, the measurement uncertainty increases at low total flowrates. Measured watercut is also within ±5% over most of the tested range.

The deviations in measured flowrates at low total flowrates are explained by the fact that the fraction measurement, which is used as input to the flowrate routine, still assumes a homogenous mixture. Work is in progress to model in-homogenous phase distributions into the fraction measurement module. This way, simply an updated version of the system software, is expected to improve the system performance.

A RANGE OF NEW MULTIPHASE METERS ARE NOW BECOMING AVAILABLE TO THE MARKET. A TEST AND QUALIFICATION PROGRAMME IS NEEDED.

At the North Sea Flow Measurement Workshop in 1991 a discussion group compiled a list of 18 different organisations currently working to develop a multiphase flowrate meter. At the Offshore Northern Seas in August 1992, five out of these eighteen (including CMR/Fluenta) announced meters available for the market.

The application of such multiphase meters can drastically change a satellite development concept. Separate testlines and manifold systems at the satellite may be omitted. The same may be the case for test separators, inlet separators and complex single phase measurement systems at the processing platform. Such drastic changes to proven technology can of course not be accepted unless the reliability of the new technology has been thoroughly qualified. In order to progress the maturity of such technology towards proven and accepted technology, it is therefore now important that the oil companies involve in test and pilot installations of multiphase meters.

The step from testing in a friendly laboratory environment on a model oil, to tough field applications on live crude is huge. In order to qualify this new technology for a wide application in future field developments, it is therefore now of the utmost importance to gain field experience on non-critical installations. It may be a costly process both to install the meters and to maintain a qualification test programme, however, the potential future cost savings should make such an investment profitable.

Field scenario studies suggest that subsea satellites is one of the most interesting applications for multiphase meters in the future. The subsea challenge is addressed in several multiphase meter development projects, and the first subsea versions are likely to be available for field testing at least by 1994. Provided that sufficient reliability of topsides meters has been verified, there will then exist a need for places where meters can be installed subsea for qualification.

Several of the multiphase meters available or in development require an upstream mixer to provide suitable measurement conditions. In our opinion, it is however not evident that there exist a multiphase mixer which will be able to create no-slip conditions and homogeneous phase distribution over a sufficiently large range of flowrates and composition. Since the overall performance of many multiphase meters will directly depend on the performance of available mixers, a test programme for evaluation of available mixers should be initiated.

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