WATER-IN-LIQUID PROBE
System for measuring Water-in-Liquid Ratio at low and high gas volume fractions

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1. ABSTRACT

A prototype dielectric on-line monitor for measurement of water cut in multiphase petroleum flow has been built. The system is a low cost and robust system capable of measuring 0-100% water cut at 3% uncertainty. The system has been tested successfully at gas volume fractions (GVF) ranging from 0% to 93%. The monitor is designed with a view to installation topside, subsea or downhole.

The measurement concept is based on dielectric measurements of the liquid in the flow at high frequency using an open ended coaxial probe. The method utilises the complex permittivity of the fluid to calculate the water cut. The instrument consists of the dielectric sensor installed in the pipe wall, an electronic unit for measuring the complex reflection coefficient and a PC for control, signal analysis, calculation of water cut and data presentation. The sensor facilitates easy installation, e.g. similar to a pressure transducer.

2. INTRODUCTION

The water production from oil producing reservoirs will normally increase during depletion. This has focused effort on the measurement of water both in the reservoir and at the surface. There are several meters on the market measuring the water-in-liquid ratio (WLR) of an oil/water mixture. Many of these are excellent instruments. However, they are all intended for liquid flow, only. A common feature is that they are based on measurement of the dielectric constant of the total pipe volume, either at high frequencies (microwaves) or at lower frequencies (capacitance/conductance). When gas is present in the flow these meters naturally suffer from high uncertainties. However, for wells with high gas contents, such as gas lifted wells and condensate wells, there is at present no automatic on-line technique available on the market. The solution has therefore been sampling followed by analysis of the liquid, which is not very practical and not at all suited for subsea or downhole applications. A novel technology for this application should therefore operate at the high void fractions (up to 98%) as well as at the lower range down to 0%.

Multi-phase meters are certainly able to measure the water-in-liquid ratio in a multi-phase flow. However, these are not low-cost instruments and the likelihood that one is installed at every single well on e.g. a manifold is generally low. In addition, the uncertainty of the water-in-liquid ratio measurement tends to increase as the GVF becomes high. This is mainly due to the fact that multi-phase meters are designed for measuring all three phases covering all practical combinations of phase fractions, i.e. they employ sensors with equal sensitivity over the whole cross-section of the pipeline.

3. MEASUREMENT SYSTEM AND EXPERIMENTAL ROUTINES

A high frequency electromagnetic wave is transmitted through an open-ended coaxial probe into the liquid film, which is located at the inner wall of the pipeline as shown in Figure 1.

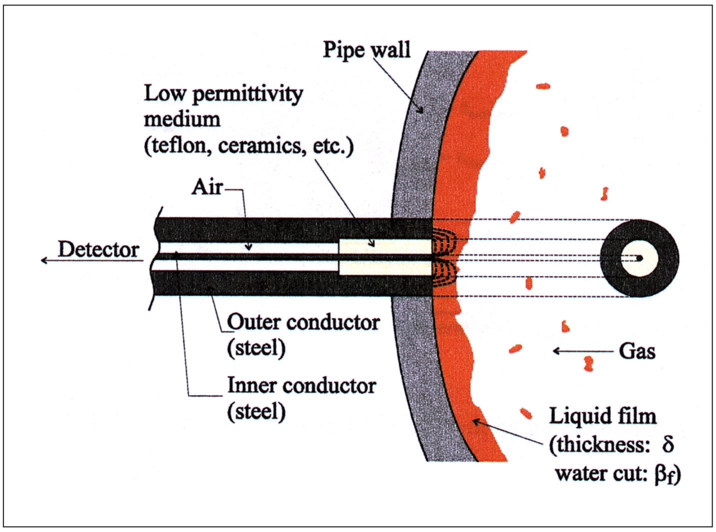


Figure 1 Open-ended coaxial probe for measurement of the relative permittivity of liquid films in multiphase flow. The mixture is assumed to consist of an oil-water liquid film, and a gas core behind the liquid. The water volume fraction of the liquid film is denoted as the water in liquid ratio, β_f, the film thickness has been given the symbol δ and the permittivity of the liquid bulk.

At the probe-liquid interface some of the electromagnetic energy is reflected. The reflected signal is dependent on the permittivity of the medium in front of the probe. The complex reflection coefficient, Γ_R, at the end of a coaxial probe depends on the complex permittivity, ε^*, of the medium the probe is in contact with:

$$\Gamma_R = \frac{1 - j\omega Z_0 C(\varepsilon^*)}{1 + j\omega Z_0 C(\varepsilon^*)} \tag{1}$$

where Z_0 is the characteristic impedance of the probe, is the angular frequency, $\omega = 2\pi f$ where f is the frequency, and $C(\varepsilon^*)$ is the fringe capacitance of the probe.

From a microwave measurement of the reflection coefficient, the relative permittivity of the medium can be determined.

At high GVFs the flow regime will approach an annular distribution, and a dielectric measurement of the liquid must therefore be performed near the pipe wall. Thus, the measurement system is based on an open-ended coaxial probe designed with a short penetration depth and installed in the pipe wall to be able to measure only on the liquid film. By this arrangement a three-phase problem can be reduced to a two-phase measurement. By proper signal analysis, the system can handle gas bubbles and thin liquid films. The sensor will facilitate easy installation, e.g. similar to a pressure transducer.

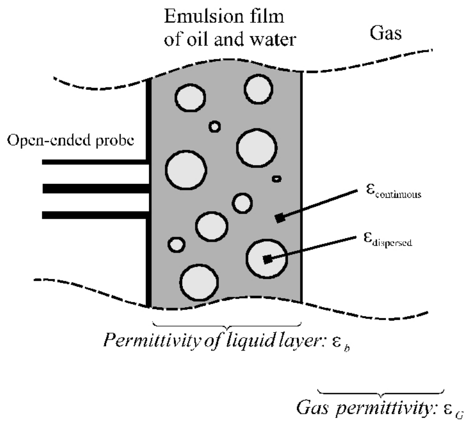


Figure 2 Schematic illustration of the permittivity measurement by an open-ended coaxial probe

The laboratory measurement system (Figure 3) consists of a microwave reflectometer controlled by a personal computer and a sensor. The sensor, an open-ended coaxial-probe, is mounted in the pipe wall of the multiphase flow line, and the reflectometer measures the reflection coefficient from the probe. The permittivity of the liquid film is then calculated from the reflection coefficient.

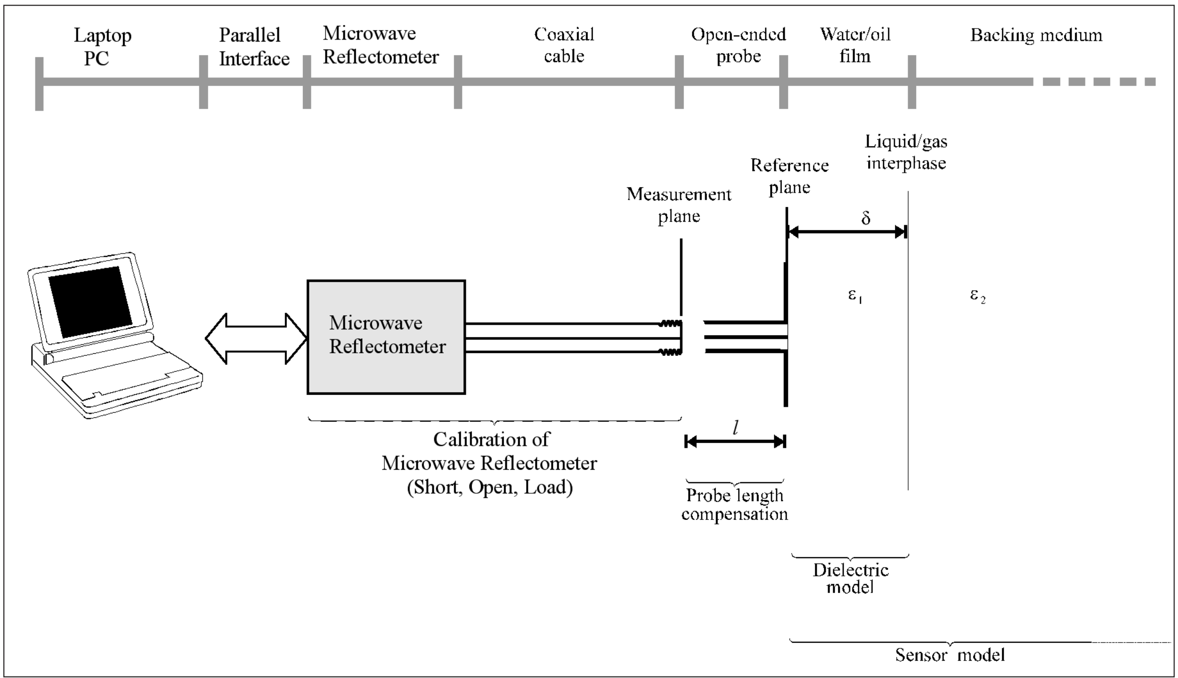


Figure 3 *Measurement procedure and sketch of the overall measurement system ($\varepsilon_1 = \varepsilon^*$ and $\varepsilon_2 = \varepsilon_G$). l in the figure is the physical length of the open-ended probe, and it can be related to the electrical length of the probe as follows: $l_e = \sqrt{\varepsilon_{coax}} \cdot l$ =where ε_{coax} is the permittivity of the medium between the inner and outer conductor of the probe.*

In determining the WLR of the oil-water emulsion film in front of the open-ended probe, the overall calibration must take the following parts into account:

- *Calibration of the reflectometer.* This must be performed to define the end of the coaxial cable as the measurement plane.

- *Probe length compensation.* This compensates for the physical length and the impedance mismatch of the probe.

- *Sensor model* which relates the reflection coefficients at the end of the probe, the reference plane, to the permittivity of the liquid film, 1.

- *Dielectric model* for calculating the water in liquid ratio of the liquid film on the basis of the permittivity of the film and the known permittivities of oil and water. Both analytical and chemometric models are developed (cf. Section 4).

Tests of the laboratory prototype system have been performed at the CMR multiphase flow loop, and the tests aim at evaluating the feasibility of this method for water in liquid ratio measurement in a multiphase flow.

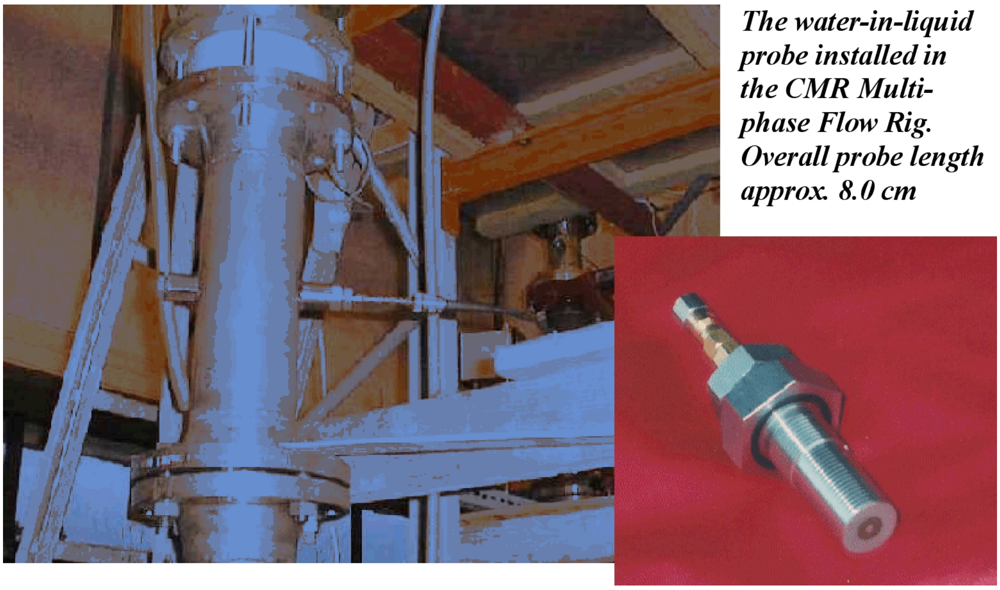


Figure 4 The sensor installation in vertical upward flow.

Figure 5 The prototype WLR system, including a dedicated microwave electronics unit, and a portable PC which is used to control the microwave electronics and the data collection and processing.

3.1 The CMR multiphase test facility

The test facility consists of a 4” diameter flow loop, a 3 m^3 separator tank, a 7.5 kW centrifugal pump and reference instrumentation for determination of phase fractions, flow rates, flow pressures and temperatures as schematically shown in Figure 6. The flow constituents are Fina Auto-diesel, salted tap water and compressed air.

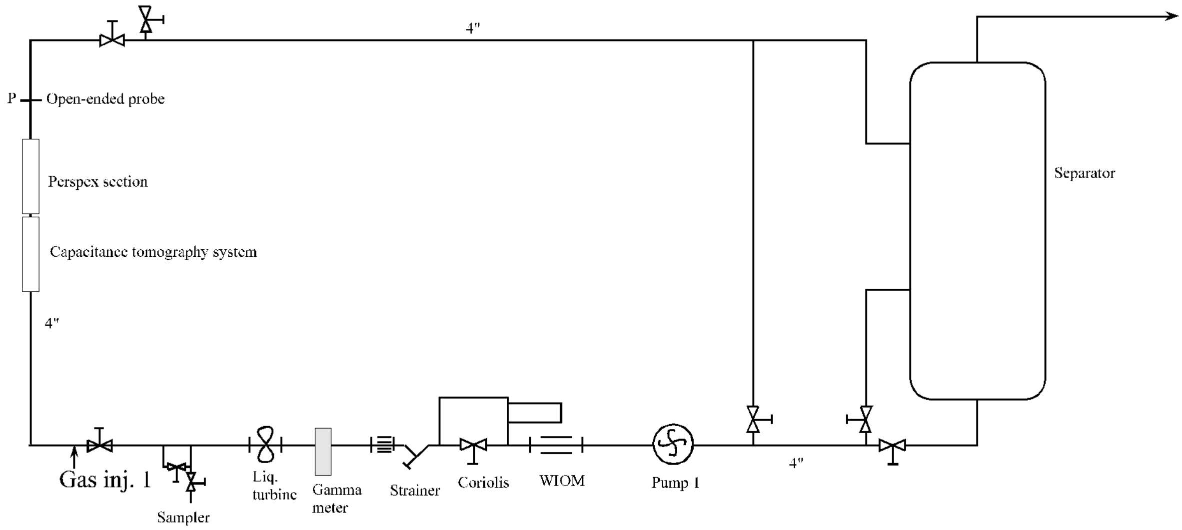


Figure 6 The CMR multiphase flow facility

The separator contains 1 m^3 of oil and 1 m^3 of water. These are separated by gravity and are fed into the loop through separate legs with a throttle valve at each leg to adjust the water in liquid ratio. Downstream of a water-oil mixing junction (T-piece), the liquid enters the centrifugal pump. The pump is, together with a downstream Daniel 4" liquid turbine meter, part of an electronic control loop connected to an automatic flow controller in the control room. This control loop is used to set the liquid flow rate to a chosen pre-defined value.

The water in liquid ratio is measured by means of a Fluenta WIOM 300 installed downstream of the centrifugal pump. The WIOM gives feedback to the throttle valves via a second automatic flow controller in the control room. By this control loop the water in liquid ratio can also be fixed at a chosen set point.

In water continuous flow the reference water in liquid ratio is determined by means of the Coriolis meter and a Krohne gamma densitometer. The Coriolis and the gamma meter measure the density of the oil-water mixture passing through the meters.

The density of oil (diesel) and (saline) water are known and the reference water in liquid ratio can then be calculated as:

$$WLR_{ref} = \frac{\rho_{Coriolis} - \rho_O}{\rho_W - \rho_O} \cdot 100\% \qquad (2)$$

where $\rho_{Coriolis}$ is the density measured by the Coriolis meter, ρ_O is the density of the oil and W is the density of the saline water. A similar expression is used to calculate the WLR from the oil/water density measured by the Krohne gamma densitometer. The average value of the WLRs determined from the Coriolis and the Krohne meter was used as the reference WLR in water continuous flow.

The air from the compressor is stored in a separate tank at a constant pressure of 10 barA. It is supplied to the test facility through a needle valve after being measured by a 1.5" orifice plate meter. There is also a control loop for the gas valve, but the flow controller is normally run in manual mode in order to decrease the response time of the adjustment of the gas injected into the loop. In this project multiphase flow at high gas fractions are emphasised. With regard to this a V-cone meter has been installed in addition to the orifice meter, for measurement of high gas flow rates[1] . The V-cone meter is mounted as part of a new supply line for injection of gas into the flow loop.

The gas is injected at the point denoted as gas injection point 1, see Figure 6

The multiphase flow passes through the vertical test section, enters a horizontal return pipeline and flows back to the separator. The gas is vented out to open air from the separator.

3.2 Reference measurements

The reference liquid flow rate measurement is provided by the Daniel 4» turbine meter which has a calibrated measurement range of 19.3-284 m^3/h. The nominal relative uncertainty in single phase water flow is 0.25%. At lower flow rates a 1.5" Micro Motion coriolis meter is used as a reference instrument. This meter has a nominal relative uncertainty of 0.2%. Since a mixture of oil and water is used the real uncertainty has been estimated by a comparison between the readings of the turbine meter, the coriolis meter and a Venturi meter. A conservative uncertainty of 2.0% is therefore used for the liquid flow rate (QLiq).

The reference gas flow rate is measured by a 1.5» orifice plate meter or a 1.5» V.cone flow meter depending on the flow rate of gas injected. Since the pressure at the gas flow meter location differs from the pressure at the point of measurement, the actual flow rate (QGas.Ref) can be calculated by the following relationship:

$$Q_{Gas.Ref} = Q_{Gas} \cdot \frac{P_{Gas}}{P_{Flow}} \tag{3}$$

The effect of changes in temperature is neglected because of the short distance between injection point and the test section. The differential pressure across the orifice plate is measured by a 0-300 mbar dP-transmitter. The uncertainty of the Orifice meter is 2.8% of full scale which is 120 Sm^3/h. The uncertainty of the V-cone meter is 1.0% of measured value at flow rates 60-230 Sm^3/h, and 2.0% at flow rates 230-750 Sm^3/h. The absolute pressure at the gas meter location (P_{Gas}) is measured by a 0-10 bar transmitter with an uncertainty of 0.05 bar. The pressure in the test section (P_{Flow}) is measured by a 0-2.5 bar transmitter with an uncertainty of 0.0125 bar. It is mounted diametrically opposite to the open-ended probe, see Figure 6.

[1] The operating range of the orifice meter is 0-120 Sm^3/h, while that of the V-cone meter is nominally 60-750 Sm^3/h. In practice, due to gas delivery restrictions and pressure losses the maximum amount of gas which can be injected into the loop is about 350 Sm^3/h.

The uncertainty of the water in liquid ratio (βf) measured by the Fluenta WIOM 300, is 1.0% absolute. This is established through calibration vs. samples of the liquid flow.

Comparative tests of water in liquid ratio determined by the Coriolis meter and samples taken in the liquid metering run indicate an uncertainty of $\pm$2% absolute.

The reference gas volume fraction is calculated using the following equation:

$$\alpha_V(\%) = \frac{Q_{Gas}}{Q_{Gas} + Q_{Liq}} \cdot 100\ \% \tag{4}$$

Using Eq. (4), the uncertainty of the reference gas volume fraction is expressed by:

$$\alpha_V(\%) = \frac{Q_{Gas}}{Q_{Gas} + Q_{Liq}} \cdot 100\ \% \tag{5}$$

After differentiating, inserting the uncertainties and manipulating the expression, we end up with a nominal uncertainty of[2] :

$$\alpha_V(\%) = \frac{Q_{Gas}}{Q_{Gas} + Q_{Liq}} \cdot 100\ \% \tag{6}$$

which is an absolute uncertainty.

It is important to note that the gas volume fraction given by Eq. (4) is the "no-slip" gas fraction, i.e. it equals the local gas area fraction only when there is zero slip between the gas and the liquid phases. This is not the case since the gas flows faster than the liquid in the vertical upward flow considered here. Hence, the reference gas volume fraction generally differs from the local gas phase fraction.

In a summary, all the uncertainties are listed in Table 1 below where the relative uncertainty indicates percentage of indicated value, while the absolute uncertainties are related to full scale, i.e. 100%.

[2] The calculation presented here is for the case of a gas flow rate giving a total relative uncertainty of less than 5%.

Parameter	Symbol	Uncertainty (Type)
Liquid flow rate	Q_{liq}	2.0% (Relative)
Gas flow rate	Q_{gas} turn down (1:4): flow rates < 30 Sm^3/h:	 3.0-5% (Relative) > 5% (Relative)
Gas volume fraction (GVF) [3]	α_V	2.0% (Absolute)
Water-in-liquid-ratio (WLR)	β_f	1.0% (Absolute) in W/O [4] 2.0% (Absolute) in O/W

Table 1 Uncertainties of the reference measurements.

4. RESULTS

The system has been continuously tested throughout the development period. The system has also been used for acquiring data in connection to the multivariate analysis to develop the chemometric models[5] . Thus the performance of the system is constantly under evaluation. At the time of printing, a more thorough performance test is on going.

The performance tests show that so far the system is capable of handling all types of multiphase flow regimes generated in vertical upwards flow from 0 to 100% WLR and 0 to 90% gas volume fraction using only one, non-intrusive sensor.

Measurement results are given in Figure 7 and Figure 8 on the two next pages.

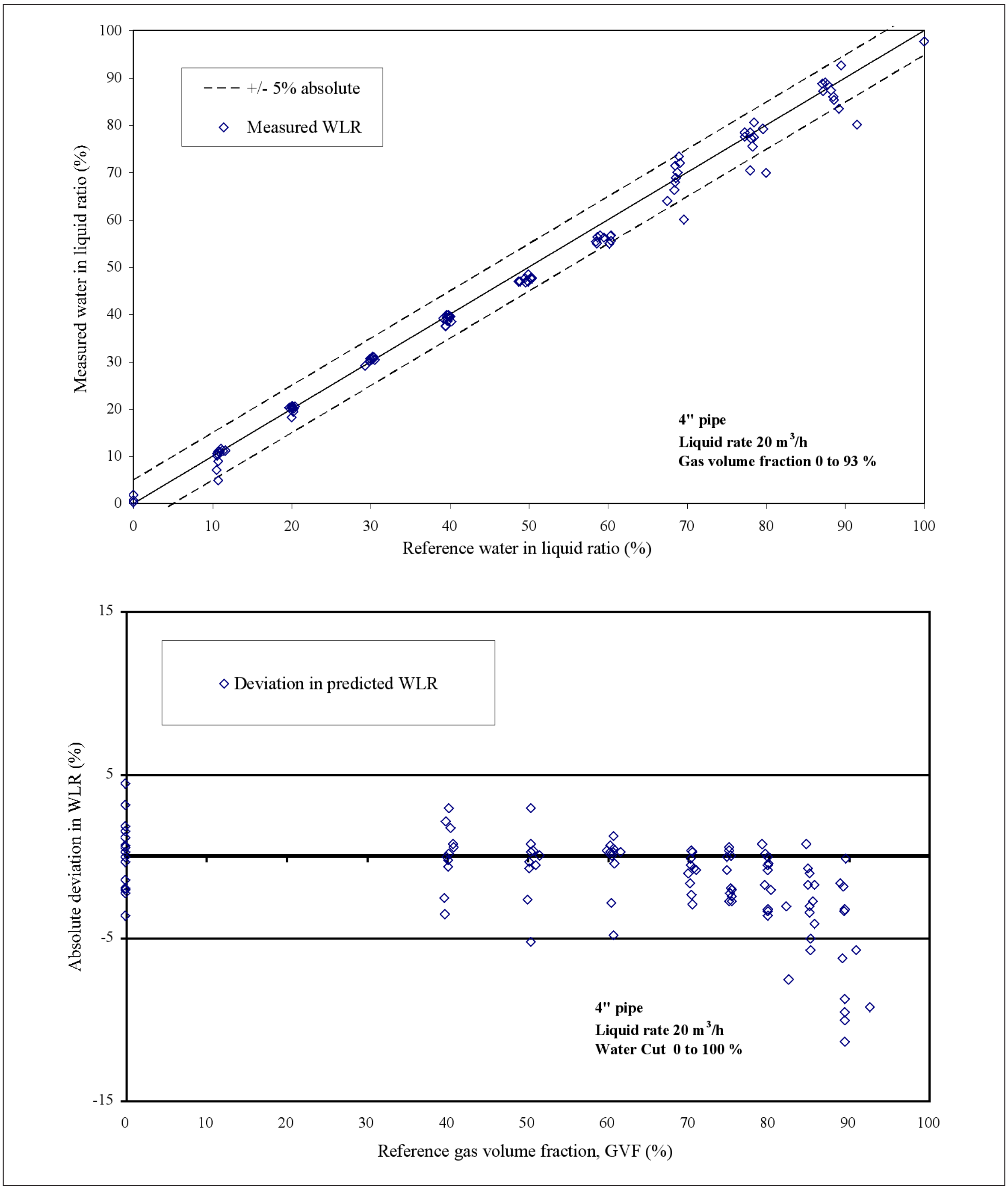
In Figure 7, a test of the analytical models used in the system. For GVF's below 80% the average deviation from reference WLR is 1.3%, the maximum deviation is 5.3%. The average deviation from reference WLR, all test point included, is 2.1 %, the maximum deviation 11.4 %. In this test the WLR varied from 0 to 100 % and the GVF from 0 to 93%.

Figure 8 shows the test of the chemometric models with new data, the average deviation from reference WLR is 0.9 %, the maximum deviation 3.8 %. In this test the WLR varied from 0 to 100 % and the GVF from 0 to 82%.

3 This uncertainty estimate refers to the "no-slip" gas fraction where there is zero slip between the gas and the liquid phases. Generally the reference gas volume fraction differs from the local gas phase fraction.

4 W/O denotes oil continuous flow while O/W denotes water continuous flow.

5 Chemometrics is the branch of the multivariate methods, which is adopted by chemists. The methods are powerful statistical techniques for extracting relevant information that exists in any interaction effects that are present between two or more variables.



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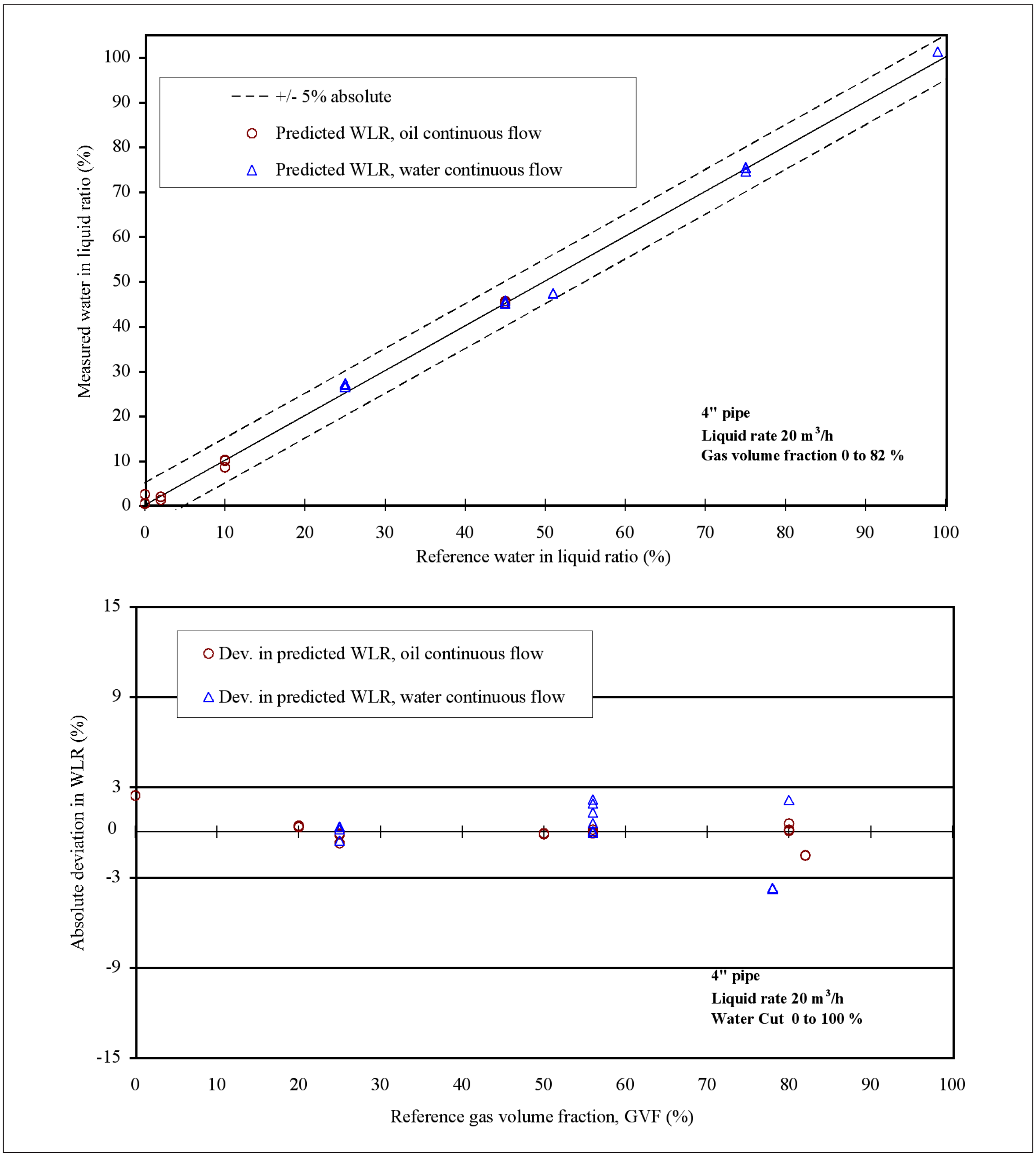

Figure 8 In a test of the chemometric models, the average deviation from reference WLR is 0.9 %, the maximum deviation 3.8 %. In this test the WLR varied from 0 to 100 % and the GVF from 0 to 82%.

5. LIQUID SAMPLING OF THE CORE AND THE FILM

This section presents the results of a preliminary experimental investigation into the Water-in-Liquid Ratio (WLR) of the core and the film of an oil-water-air flow in the annular-mist regime.

5.1 Introduction

In annular-mist flow, the proposed water cut monitor provides an estimate of the Water-in-Liquid Ratio (WLR) for the liquid film only. In order to estimate the overall WLR for an annular-mist flow, it is necessary to relate the WLR in the liquid film, as measured by the water cut monitor, to the WLR of the liquid conveyed as droplets in the gas core. Accordingly, a sampling device was designed and constructed which allows samples of liquid to be taken from the core and film of an annular-mist flow. The sampling device was mounted at the top of the vertical working section of the flow loop at CMR in which oil-water-air flows in the annular-mist regime can be established.

A series of experiments were carried out to obtain liquid samples from the core and film at the following flow conditions:

1. The total liquid flow rate into the working section was maintained at a constant value of 10 m^3/h.
2. The air flow rate was set at 350 m^3/h.
3. The water-in-liquid ratio β_{f_Ref} of the liquid entering the working section, prior to the point at which the air was injected, was varied in the range 20% to 90%.

At each flow condition the flow was allowed to stabilise prior to samples being taken. Independent measurements indicated that the overall gas volume fraction was always approximately equal to 96%. Images obtained, where possible, using a capacitance tomography system showed that for this value of gas volume fraction the flow was always in the annular-mist regime.

5.2 Experimental set-up

In the vertical test section shown in Figure 6, the probe pipe section was replaced by an identical pipe section containing the core and the film sampling devices. A schematic of the sampling section is shown in Figure 9.

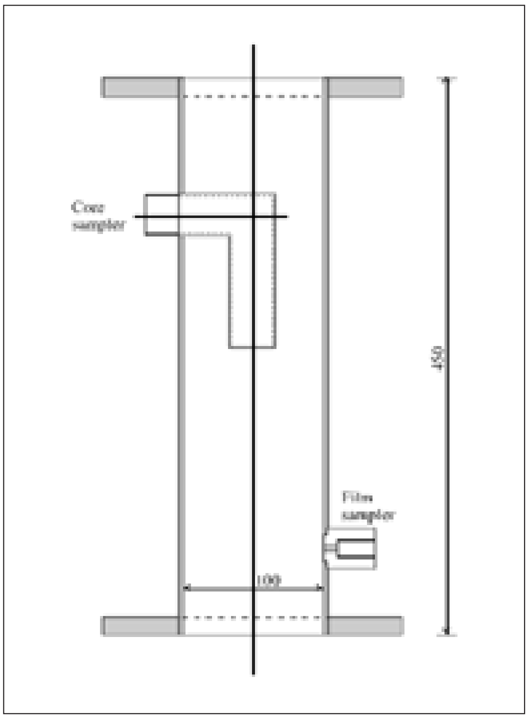

Figure 9 Schematic of the sampling section

5.3 Results of Sampling

At each of the flow conditions described above, liquid samples of approximately one litre in volume were bled into sampling vessels from both the core and the film. Any air that entered the sampling vessels was vented to atmosphere. In order to minimise any disturbance to the liquid film, the rate at which liquid was bled from the film was always less than 0.5% of the total liquid flow rate. Following collection of the samples, the oil and water were allowed to separate out in the sampling vessels under the influence of gravity. The water-in-liquid ratios β_{f_Core} and β_{f_Film}, for the liquid in the core and film respectively, were then obtained by measuring the oil and water levels in the appropriate sampling vessels.

In Figure 10, β_{f_Core} and β_{f_Film} are plotted against β_{f_Ref}. It is clear from Figure 10 that the values of β_{f_Core} and β_{f_Film} are always very close to the value of β_{f_Ref} .

Figure 11 shows a plot of β_{f_Core} minus β_{f_Film} versus β_{f_Ref} for all of the flow conditions investigated. It is clear from Figure 11 that the value of β_{f_Core} is always within 2% of the value of β_{f_Film}. This result is very encouraging because it implies that the WLR in the film and in the core are approximately the same, which in turn implies that a good estimate for the overall WLR for an annular-mist flow can be obtained by measuring the WLR in the liquid film alone. Further work should be carried out to confirm that this result is valid for a wider range of flow conditions.

Note that results obtained by Zabara et al. [5] suggest that, under many conditions, the majority of liquid in a vertically upward, cocurrent annular-mist flow is conveyed in the film rather than in the gas core. Consequently, measurement of the WLR in the film might be expected to give a value representative of the overall WLR even if flow conditions are encountered where there is a difference in the values of β_{f_Core} and β_{f_Film}.

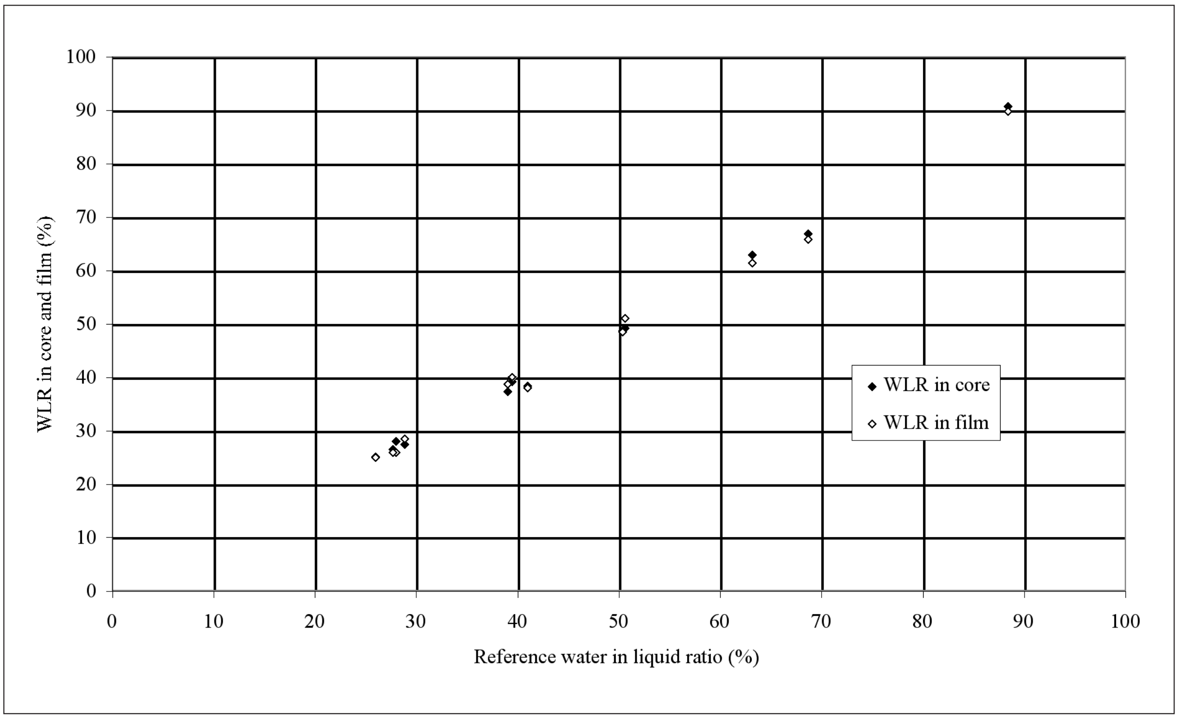

Figure 10 Water in liquid ratio determined by sampling of the core and the film, respectively, plotted versus the reference water in liquid ratio determined by sampling of the liquid phase. The water is saline water of conductivity 9.05 S/m.

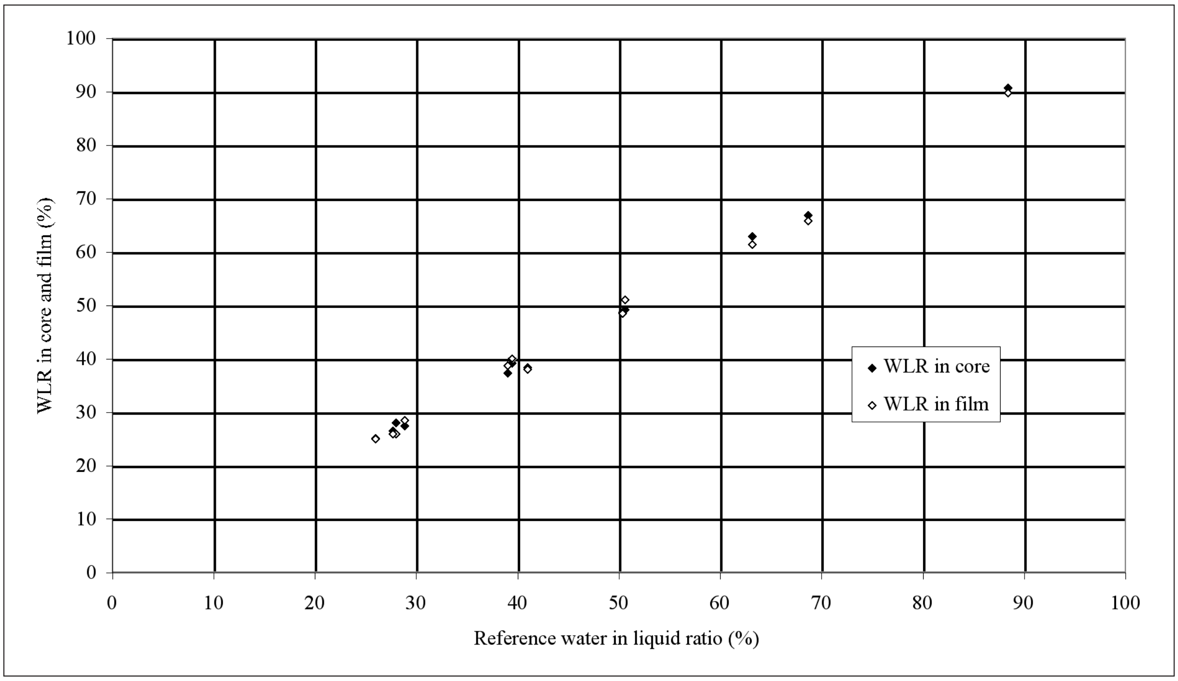

Figure 11 Absolute deviation in the water in liquid ratio between the samples of the core and the film plotted versus the reference water in liquid ratio determined by sampling of the liquid phase. The water is saline water of conductivity 9.05 S/m.

6. DISCUSSION AND CONCLUSION

A prototype WLR probe measurement system has been tested by mounting a probe in the pipe wall in contact with the fluid at the CMR multiphase test facility. The results show that an open-ended coaxial probe can be used for on-line measurement of the water in liquid ratio in a multiphase flow and that it is sufficiently accurate across a wide range of gas-liquid ratios in vertical oil-water-gas pipe flows. The results from the tests are promising, and the feasibility of the technique has been proved. Because of the simplicity of the probe this makes it a very powerful tool for monitoring of oil-water-gas processes.

The following main conclusions can be drawn for most of the test points in the range 0-100% water in liquid ratio:

1 In oil/water flow with no gas the water in liquid ratio is measured well within ±5% absolute deviation compared to the reference.

2 The water in liquid ratio can be measured within ±5% absolute deviation compared to the reference for gas fractions in the range 0-85% using analytical permittivity models.

3 For gas fractions higher than 85% the uncertainty increases, and is also dependent on whether the flow is oil- or water-continuous. For gas fractions in the range 85-95%, the water in liquid ratio is measured within ±10% absolute deviation in oil-continuous flow, and ±12% absolute deviation in water-continuous flow. At all test conditions good repeatability of the measurements were found.

4 In general, and particularly at gas volume fractions higher than 85%, the measured water in liquid ratios are underestimated compared to the reference water in liquid ratio when using analytical models. The main reason for this is the presence of gas in the film in front of the probe, or the appearance of a film thickness lower than the sensitivity depth of the probe at very high gas volume fractions.

5 With the chemometric models the uncertainty can be narrowed in to 3% absolute for GVF's from 0 to 82%. The tendency to underestimate the WLR is not seen here.

6 At the operating frequency in question, it has been found that the measured water in liquid ratios are not significantly affected by the increased water salinity as long as the conductivity of the water is known. The permittivity of the water, for the dielectric model, can then be determined.

In addition the following can be stated:

7 A preliminary experimental investigation into the WLR of the core and the film of an oil-water-air flow in the annular-mist regime implies that the WLR in the film and in the core are approximately the same. This in turn implies that a good estimate for the overall WLR can be obtained by measuring the WLR in the liquid film alone. Further work should be carried out to confirm that this result is valid for a wider range of flow conditions.

7. ACKNOWLEDGEMENTS

The development work performed to build the WLR-probe measurement system is a team effort constituting scientists who are currently or have been working at Christian Michelsen Research AS, Dept. of Industrial Instrumentation. Academic spin off from the development work has been 3 Ph. D. theses and 2 M.Sc. theses.
The development has been supported continuously by British Petroleum (now BP Amoco) and the Norwegian Research Council since the first project was initiated in 1996.

8. FURTHER WORK

CMR is currently moving on with the building of an industrial prototype, which is going to be tested at a field location next year. Also, projects for building of subsea and downhole versions are started. A main task in the latter two projects is the development of state of the art miniature microwave- and detector electronics (ASIC design) in co-operation with University of Bergen, Department of Physics. A successful development of miniaturised electronics will render possible a very compact sensor/detector unit for installation in almost any process topside, subsea or downhole.

The development of a subsea WLR probe system is currently supported by the Norwegian Research Council and Kongsberg Offshore AS (KOS)

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