

Challenges with salinity measurements in multiphase flow metering

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1. Introduction

In situ measurement of multiphase flow over a wide range of flow conditions is not a trivial task and imposes various challenges for multiphase meters. Although the metering technology has evolved over the last decade, there is a potential for improvement in certain areas. Experience shows that one of the main sources of uncertainty for multiphase meters is insufficient/incorrect knowledge of fluid properties: such as density, viscosity and permittivity. In multiphase meters based on the measurement of flow permittivity, the measurements are especially affected by changes in the salinity of the water phase. This is due to the strong relationship between the water permittivity and the conductivity and hence the salinity of the water. The measurements are predominantly affected by this dependence in water continuous flow.

Traditionally, the salinity has been obtained from a water sample, and the result of the lab analysis was used as an input to multiphase meters. The response time with this approach is limited by the sampling interval and taking a representative sample was not always possible. In order to reduce the response time and the uncertainty of the multiphase meters outputs, the requirement for the modern multiphase flow meters is to be independent of changes in water salinity. In addition, the salinity of the water phase is a valuable parameter for flow assurance purposes.

In order to meet the market needs in multiphase and wet gas metering Roxar has developed dedicated sensors for salinity measurement for a broad range of multiphase flow conditions as shown in Figure 1. These sensors are based on various principles but they all employ microwave technology. The current portfolio for a salinity measurement system includes the following tools:

- The formation water detection function in the Roxar Wetgas meter: designed for the detection of the onset of the formation water production in high gas volume fraction (GVF) applications. It is based on a two-parameter measurement of the resonant frequency and Q-factor of the microwave cone resonator [1, 2].
- The microwave surface sensor designed for the salinity measurement in wet gas flow at high to ultra high GVF, i.e. a wet gas or a multiphase flow with high gas volume fraction. This sensor is designed for use in both the Roxar Wetgas meter and Roxar Multiphase meter and it is a ceramic cavity resonator mounted in the wall of a meter body [3, 4].
- The three-probe differential transmission sensor, further referred to as microwave salinity probe: for measuring the salinity of the water in a water continuous multiphase flow. The sensor is based on a two-parameter measurement, i.e.

measurement of differential attenuation and phase. This paper focuses on the development work of this sensor and the challenges that have to be overcome related to gas-liquid three phase flow.

- Roxar is also developing a technology for measuring the salinity of water in oil continuous multiphase flow. A patent application has been filed.

The operating envelop of the salinity measurements is illustrated in Figure 1. Note that the formation water detection is not depicted in this figure, as this is a functionality within the Roxar Wetgas meter and does not require any additional hardware. Also note that values of GVF in Figure 1 should be considered only as the indicative of the boundaries between different flow regimes and may be different for actual meters and applications.

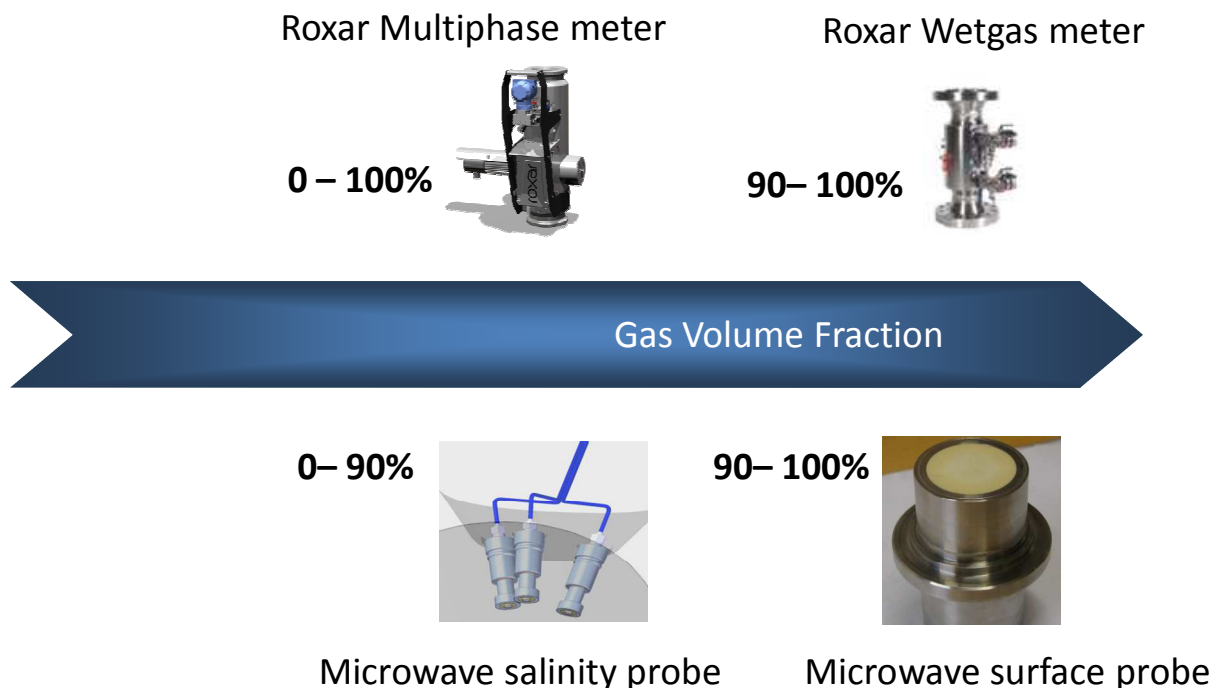


Figure 1. Metering equipment provided by Roxar and the corresponding salinity sensors.

The microwave ceramic sensor can calculate an absolute salinity value based on a two-parameter measurement of the resonant frequency and Q-factor. This sensor is to be used with Roxar Wetgas meter, where the $GVF > 90\%$ and the absolute amount of water is small. The lower limit of the operating range is defined by the amount of gas to ensure low-loss conditions and the existence of a resonance peak.

With the decrease in GVF the flow transforms from wet gas to multiphase and this brings a new challenge for a metering technology. For a multiphase flow with significantly higher amounts of water, the resonator-based sensors are not feasible to use. In order to be able to measure salinity in water continuous flow over a wide range of operating conditions, Roxar has developed a transmission based microwave salinity probe. This sensor consists of three antennas, of which one is for transmitting and the other two are for receiving. The sensor measures the effect of the flow on the propagation of the microwave signal in the

volume between the antennas. The salinity of the water phase and the local water-liquid ratio can then be calculated.

The results of the initial development stage and basic theory behind sensor principles are given in [5]. Currently, the sensor design and algorithm development work has been finalised. Several flow tests have been performed, which indicate that the developed sensor is capable of measuring conductivity of the water phase for multiphase oil/gas/liquid flows and can improve the performance of the multiphase meter. The upper limit of the operating range of this sensor is defined by the onset of annular dispersed flow regime, which is specific to wet gas flow. The operating envelopes of both transmission sensor and ceramic sensor overlap, which ensures that salinity can be measured for all possible gas volume fractions as depicted in Figure 1. This sensor can be considered as an additional functionality, which improves the performance of the multiphase flow meter and adds additional flow monitoring capabilities.

This paper summarises the main highlights of the microwave salinity probe development process and addresses the difficulties in measuring conductivity in multiphase gas-liquid flows. First, the measuring principle of the Roxar microwave salinity probe and the physics behind the technology are discussed. Secondly, the challenges in the salinity measurement, which are generic to gas-liquid three-phase flow, are outlined. Next, based on actual flow tests the data processing techniques are discussed. The developed algorithm is further used to calculate conductivity and provide an indication of the measuring uncertainty. The paper ends with conclusions and suggestions for the future work.

2. Theoretical background

The permittivity of a multiphase mixture depends on the permittivity of the components and the actual distribution of the fluids in the measurement cross-section of the pipe. Because the permittivity of water depends on the conductivity, the permittivity of a mixture of water, oil and gas then also contains information on the conductivity. The Roxar salinity sensor is based on measuring the complex permittivity of the mixture in order to obtain the conductivity of water.

The water molecule is polar, i.e. it has a permanent dipole moment, which means that the real part of the permittivity of water is high compared to that of both oil and gas. Therefore the permittivity of a water-continuous mixture is dominated by the permittivity of water and the volume fraction of water. If the water contains salt, the real part of permittivity is slightly reduced, but the imaginary part is increased significantly making the water even more dominating. As a first approximation the oil droplets and gas bubbles are considered as void in the water host. To find the conductivity of the water from the mixture permittivity one needs to perform a two-parameter measurement. There are several options as described in Sec. 2.5.4 of [6]. These are e.g. measuring the Q-factor and resonant frequency of a resonator, the attenuation and phase shift with a transmission sensor, or measuring one parameter at several frequencies. Because a water-continuous mixture, where the water is conductive, is typically a high-loss medium for electromagnetic waves, the resonator method is not so well suited. The Roxar salinity sensor is therefore chosen to be a transmission sensor, where the propagation of electromagnetic waves between small closely spaced antennas is measured.

To cancel the effects of the antennas, and all other external factors, differential transmission is used. One antenna is used for transmission, and two antennas at different distance are used for reception. The difference in the received signals is then caused by the difference in propagated distance.

The basic operation can be understood based on plane wave theory, i.e. how plane waves are affected by the permittivity of the medium. To estimate the permittivity of the medium, one needs to know the permittivity of the constituents. The permittivity of water is described by the well known Debye relation

$$\varepsilon_r = \varepsilon'_{r\infty} + \frac{\varepsilon'_{rs} - \varepsilon'_{r\infty}}{1 + j2\pi f\tau} = \varepsilon'_{rd} - j\varepsilon''_{rd} \quad (1)$$

where the subscript r means that values relative to the permittivity of vacuum are used, and f is the frequency. Values for the static permittivity ε'_{rs} , the infinite frequency permittivity $\varepsilon'_{r\infty}$, and the relaxation time τ can be found in the literature. In the frequency range of interest (up to a few GHz) the real part is in the order of 80, and the imaginary part is far smaller. When water has ionic conductivity because of salt content, the imaginary part gets an additional component:

$$\varepsilon_r = \varepsilon'_{rd} - j\left(\varepsilon''_{rd} + \frac{\sigma}{2\pi f\varepsilon_0}\right) \quad (2)$$

where ε_0 is the permittivity of vacuum ($8.854 \cdot 10^{-12}$ F/m) and σ is the conductivity. The $1/f$ -dependence of the conductivity component means that the imaginary part of the permittivity of water will be far larger at low frequencies than at high frequencies and dominating over the real part even for a low salinity. This will also be the case in a water-continuous mixture.

The permittivity of oil and gas can be estimated from equations found in the literature. The values are far lower than for water, which are roughly 2.1 for oil, and <2 for gas, and the exact values have therefore little effect on the permittivity of the mixture ε_m , which can then be estimated by a mixture equation, e.g. the Bruggeman equation. For a thorough review on mixture equations see [7].

The electric field of a plane electromagnetic wave propagating in a medium is described by the equation

$$E = E_0 \cdot e^{-jkx} = E_0 \cdot e^{-jk'x} \cdot e^{-jk''x} \quad (3)$$

where k is the wave vector and x is the propagated distance. It is seen that the real part of k determines the phase of the wave, while the imaginary part determines the attenuation. The wave vector is given by

$$k = k' - jk'' = \frac{2\pi f}{c} \sqrt{\varepsilon_{mr}} = \text{Re}\left\{\frac{2\pi f}{c} \sqrt{\varepsilon_{mr}}\right\} - j \text{Im}\left\{\frac{2\pi f}{c} \sqrt{\varepsilon_{mr}}\right\} \quad (4)$$

Introducing the real and imaginary part of the permittivity gives

$$k' = \frac{2\pi f}{c} \sqrt{\frac{\varepsilon'_{mr}}{2} \left(1 + \sqrt{1 + \left(\frac{\varepsilon''_{mr}}{\varepsilon'_{mr}}\right)^2}\right)}, \quad k'' = \frac{2\pi f}{c} \sqrt{\frac{\varepsilon'_{mr}}{2} \left(-1 + \sqrt{1 + \left(\frac{\varepsilon''_{mr}}{\varepsilon'_{mr}}\right)^2}\right)} \quad (5)$$

A study of this equation shows that in a high-loss situation ($\epsilon''_{mr} \gg \epsilon'_{mr}$) the following approximation can be used

$$k' = k_0 \sqrt{\frac{\epsilon''_{mr}}{2}}; k'' = k' \quad (6)$$

where k_0 is the wave vector in vacuum. This means that both the phase and the attenuation depend only on the imaginary part of the permittivity. Measuring both therefore does not give the extra independent information expected from a two parameter measurement. This means that the real and imaginary part of the permittivity must be of the same order of size, or the imaginary part smaller than the real part, for the two-parameter measurement to work. Because of the frequency dependence of the conductivity component of the imaginary part of the permittivity of water, the ratio $\epsilon''_{mr} / \epsilon'_{mr}$ also depends on the frequency so that it decreases with increasing frequency. This means that the measurements of phase and attenuation must be performed at a high enough frequency to yield independent information. This is illustrated by the graphs in Figure 2, where the phase and attenuation of a plane wave have been calculated for a set of different conductivities and water-liquid ratio (WLR) values at two different frequencies. For high conductivity and WLR the frequency should be 1 GHz or preferably even higher for the two-parameter method to give good resolution.

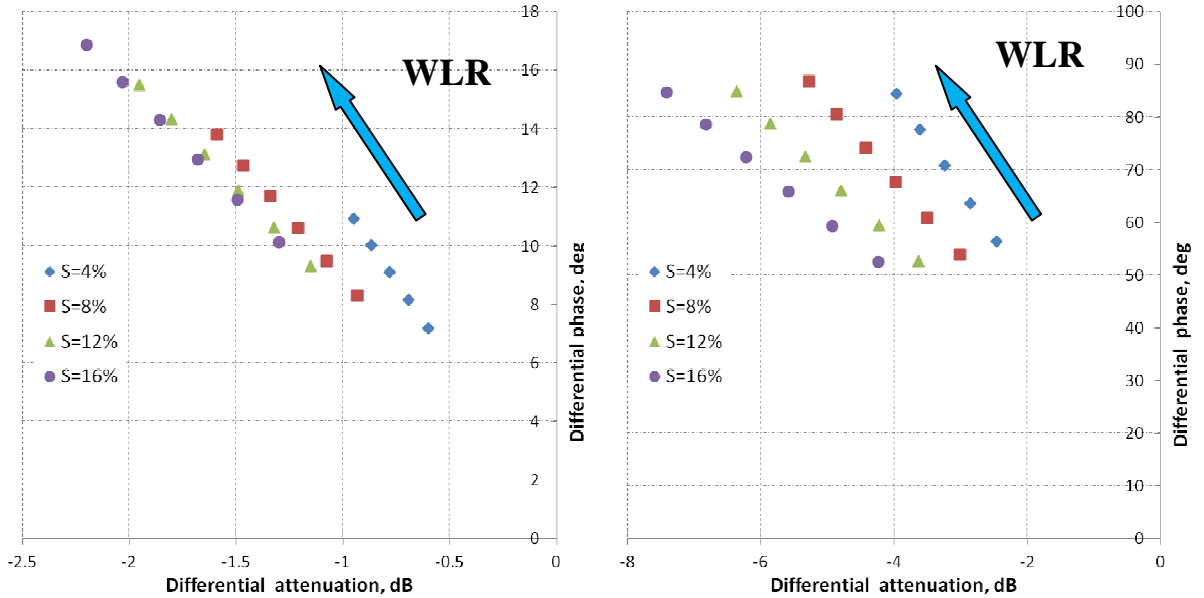


Figure 2. Differential attenuation and phase for different WLR and salinity from the plain wave theory (differential distance 1cm). Radiation frequency 0.1GHz (left) and 1GHz (right).

As mentioned above, it is also possible to perform e.g. phase measurements only, but on at least two frequencies. The reason of this choice would be the claim that phase measurements are always more accurate than measurements of attenuation, which is true in some applications of free-space transmission sensors. In that case one frequency must be in the high-loss region and the other in the low-loss region to yield independent information.

Because the transition from high-loss to low-loss depends on the conductivity and water volume fraction (WVF), these frequencies must be changed with the conditions, or the lowest frequency must be very low to always be in the high-loss region. Because the differential phase measured at a low frequency is very small due to the large wavelength, this is very impractical. Roxar experience does not support the claim of phase measurements being more accurate than measurements of attenuation in this application, hence measuring both phase and attenuation at a high frequency is a clearly preferred choice.

In practice other phenomena also affect the measurements than explained by the plane wave approximation. One phenomenon is spherical spreading, i.e. the antenna transmits spherical waves, not plane waves. Another phenomenon is related to near-field effects. In the region around an antenna there are non-propagating reactive fields. The size of this so-called near-field region depends on the permittivity of the mixture, and may be significant compared to the distance between the antennas, when the local gas content is high. Another effect is the heterogeneity of the mixture, i.e. there may be a significant difference in the local WVF in the paths to the two antennas. This effect depends on e.g. the flow velocity, GVF, pressure, WLR and viscosity. Another effect comes from the influence of the pipe. The upper end of the GVF range for the sensor is partly defined by when the mixture is no longer a high-loss medium. Then reflections from the pipe walls, the cut-off frequency and propagating wave modes affect the measurements. These phenomena make the measurement situation far more complex than described by the plane wave theory alone, and call for advanced signal processing, and the use of more than two input parameters. However, the plane wave theory describes the basic underlying physics, which the measurement method is based on. The most significant consequence is the need of a high enough measurement frequency.

3. The sensor

The prototype which was introduced in [5] consists of one probe with three small closely spaced antennas in a triangular pattern. One antenna is used for transmitting and the other two for receiving. The receivers are at different distances from the transmitter. The phase shift and differential attenuation are measured, i.e. the difference between the two received signals. In this way no extra reference is needed, and the characteristics of the antennas are eliminated. The same concept has been maintained, except for the probe. A small dedicated high-pressure probe with a single antenna has been developed for this purpose (Figure 3).

The new antenna has a PEEK insulator facing the flow instead of glass or ceramic making it more efficient due to lower permittivity. Three such antennas are mounted in separate locations in the meter body, which is preferred to a single large cavity both from a mechanical integrity and sealing point of view. In addition, this antenna can be used on all pipe sizes, and has made it easier to find the optimal geometry and distances between antennas. The sensor design and the optimal distance between antennas have been extensively studied theoretically, by simulations using HFSS (High Frequency Structure Simulator), and from multiple tests in the lab and flow loops.

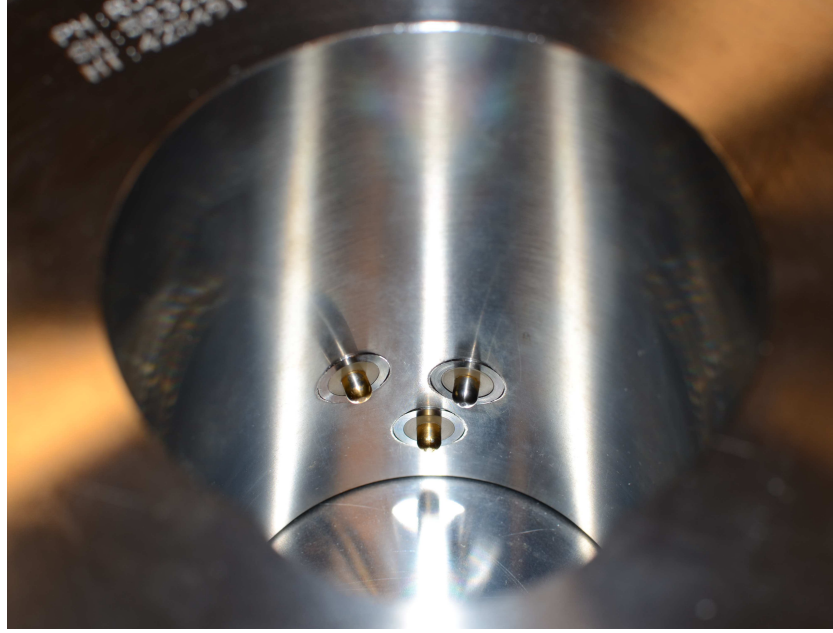


Figure 3. Microwave salinity probe installed in a spool piece (ID=87mm) for static laboratory test.

4. Conductivity measurement with microwave salinity probe

The measured differential attenuation (ΔA) and the differential phase ($\Delta\phi$) depend on the complex permittivity of the multiphase mixture, which in turn is the function of water salinity and local water volume fraction

$$\Delta A = \Delta A(S, WVF) \quad (7)$$

$$\Delta\phi = \Delta\phi(S, WVF) \quad (8)$$

Note that the local water volume fraction corresponds to the amount of water in the volume between the antennas and it is not equal to bulk water volume fraction. However, local water volume fraction is usually correlated to the bulk water volume fraction.

For two-phase liquid-liquid flows (without gas) equations (7) and (8) provide accurate predictions of water salinity. With a known salinity, the conductivity can be calculated using special models, e.g. section 2.3.2 in [6]. Once no gas is present, the phases are normally well-mixed and the flow, which is homogeneous, is described well by the Bruggeman equation. In this case, the conductivity is simply given as

$$\sigma = \sigma(\Delta A, \Delta\phi) \quad (9)$$

The presence of gas, which is the case for multiphase flow, dramatically changes the situation. In this case, even if the gas fraction is small, the phases cannot be considered as homogeneously distributed, which limits the usage of the mixing formulas. This is illustrated in Figure 4 below, where the typical sensor response is given for a relatively low gas content. One can note significant variation of the measured signal, which was not observed on the data for the similar flow conditions (conductivity, water-liquid ratio, pressure and temperature) at pure liquid flow. This is due to explicit effect of the gas phase on the sensor measured outputs. Even if the gas fraction is small, there could be different flow scenarios corresponding to the actual phase distributions, which result in absolutely different sensor

response. In particular, gas bubbles can be located in either of the flow paths between the antennas, can cover the antenna fully at the moment of measurement or in the extreme case there could be no liquid at all in a measurement volume. The variation of the signal will be affected by the size of the bubble: for homogeneously distributed dispersed bubbly flow the variation of the signal will be lower. However, it will still be significant compared to pure liquid flows, as the characteristic size of an oil droplet in water is significantly smaller than the typical bubble size.

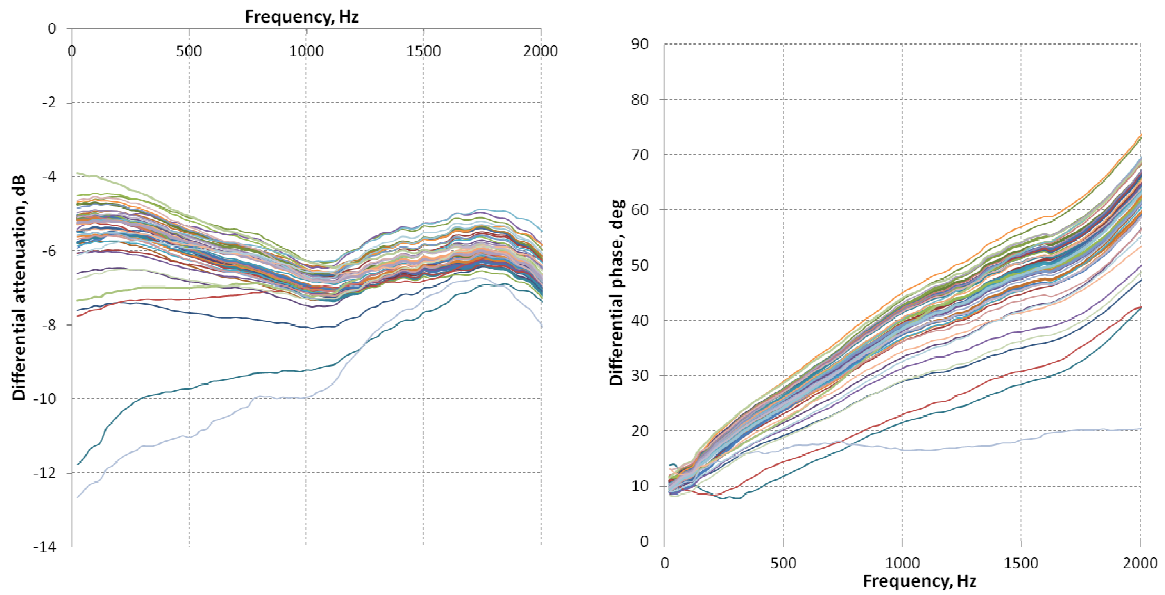


Figure 4. Example of sensor response for three-phase flow. Differential attenuation sweeps (left) and differential phase (right) at GVF=25%.

The effect of gas has a direct impact on the output of the microwave salinity probe and requires special data processing techniques, such as optimal averaging, filtering and identification of extremes, etc. This is further illustrated in Figure 5, where the actual sensor response at a fixed frequency is compared for two-phase and three-phase conditions.

For two-phase liquid-liquid flow, as it follows from the plane wave theory, the output of the sensor, which is represented in Figure 5 (left) by differential attenuation and differential phase shift at 1GHz frequency, is defined by conductivity (or salinity) of water and local water volume fraction. The plotted differential attenuation and phase are obtained from averaging transient data over a certain time interval. The conductivity can then be easily predicted by using equation (9).

Once the gas is introduced in the flow, the actual sensor response is biased, as the conditions, which correspond to certain conductivity at 100% liquid flow may produce the same sensor output as for lower conductivity and different gas content. Hence, the conductivity cannot be calculated using a two-parameter approach due to the ambiguity of the sensor response. The presence of gas in fact introduces an additional unknown which needs to be taken into account by using a dedicated modelling approach.

The output of the sensor is affected not only by the bulk gas volume fraction but also by the actual interface between liquid and gas in the volume between antennas. This

distribution, which is referred to as a local flow regime, is defined by volumetric gas content, actual velocities of the fluids, operating pressure and to a certain extent by the pipe diameter. Note, that this local flow regime is different from the bulk flow regime observed in a pipeline. Accounting for the flow regime impact is not a trivial task, as the temporal variation of the gas-liquid distribution in the measurement volume of the microwave salinity probe is not easily predicted neither theoretically nor numerically. The experimental data is needed in order to understand how the actual flow conditions affect the interaction of microwave signal with gas-liquid interface and outputs of the sensor.

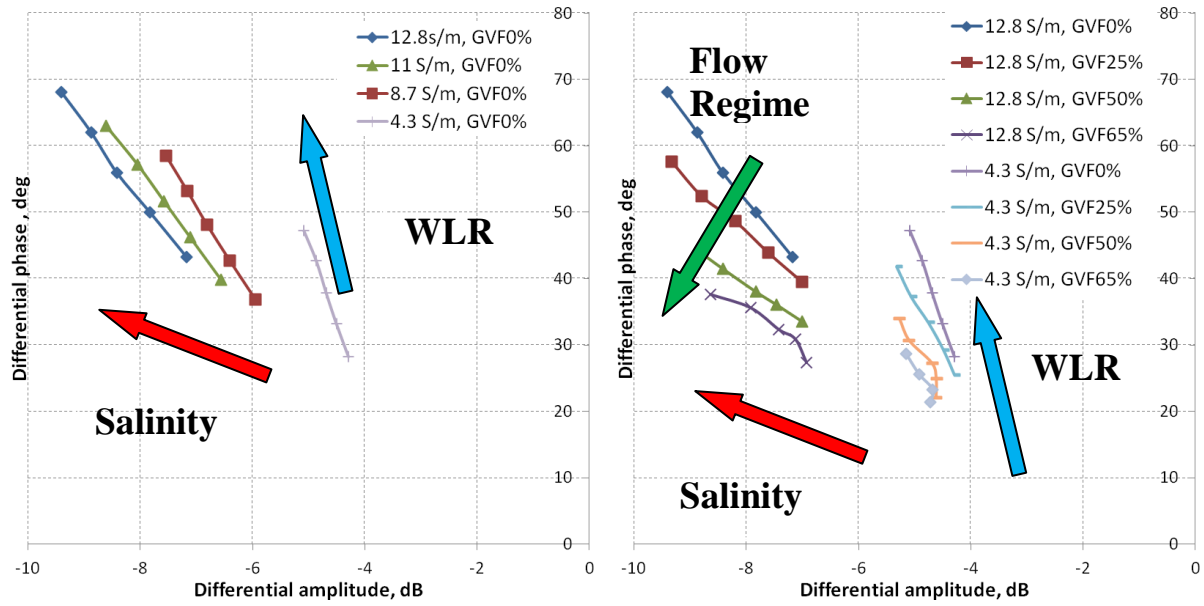


Figure 5. Illustration of the modelling challenge for three-phase gas-liquid flow. Data corresponds to low pressure testing of an earlier version of the sensor. Differential attenuation and the phase are plotted at 1GHz. WLR changes from 60% to 100%.

These phenomena are not specific to the salinity measurements, but rather represent general challenges in performing measurements in non-uniform multiphase flows. The effect of pressure on the sensor outputs is illustrated in Figures 6-7. The results correspond to data at 80% GVF at 1750MHz. Variation of the signal for a fixed pressure is due to a different water-liquid ratio. One can observe that at sufficiently high pressures the changes in differential attenuation and differential phase become less dependent on pressure. This is due to better mixing of the flow, which will be explained in more detail in Section 6 of the paper. The volumetric flow rates have a certain impact on the sensor output as well.

The resulting equation for calculation of conductivity in a three-phase flow is hence given by

$$\sigma = \sigma(\Delta A, \Delta \phi, \text{Flow regime}) \quad (10)$$

Therefore, in order to calculate conductivity in three-phase flow one needs to account for the effects related to actual flow conditions inside the multiphase meter. The way this information is obtained in the Roxar microwave salinity probe constitutes the major part of the developed technology. Advanced modelling methods and software have been used to identify the optimal set of variables to be included in the models.

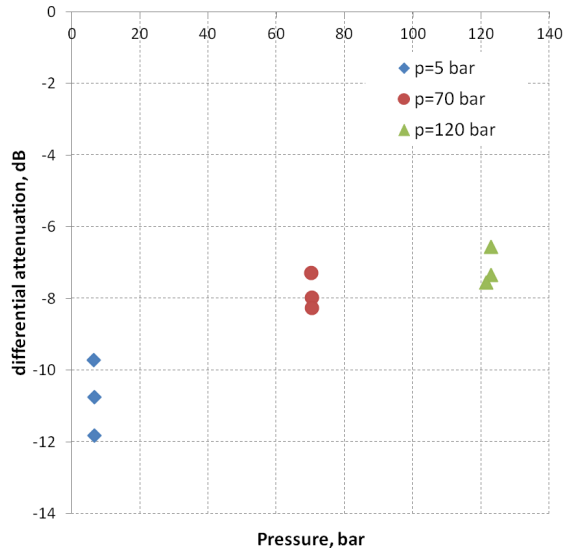


Figure 6. Differential phase as a function of pressure. Data correspond to GVF 80% are plotted at 1750MHz.

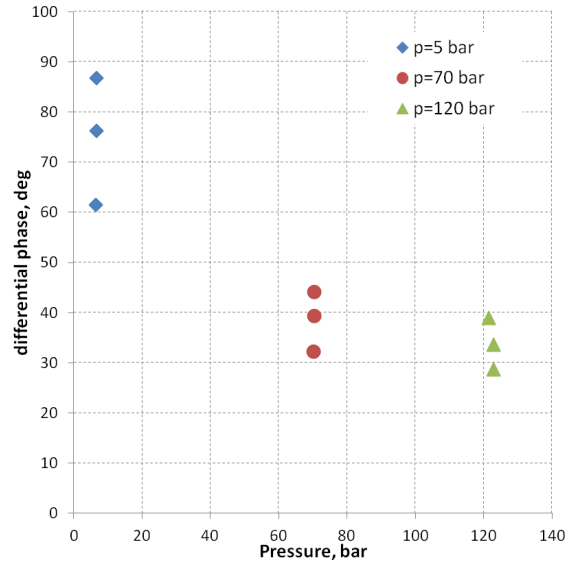


Figure 7. Differential attenuation as a function of pressure. Data correspond to GVF 80% are plotted at 1750MHz.

5. Test results

The performance of the microwave salinity probe has been evaluated via multiple flow tests. These include flow testing at Christian Michelsen Research centre in Bergen, Norway at low pressure, where both the sensor configuration and the modelling approach have been optimised. High pressure testing has been performed at K-lab, Statoil's metering and technology laboratory at Kårsto, Norway.

The results for a sensor installed in a 87mm spool piece are presented in Figure 8 where the calculated conductivity for tested pressures is plotted against reference values of conductivity. The conductivity changes from 2 S/m to 14 S/m within the tested a temperature range of 15-60°C.

The demonstrated performance of the sensor both at low and high pressure is given in Figures 9 and 10. The results indicate that the developed sensor can measure the conductivity of water with an absolute uncertainty less than 0.5 S/m and lower relative uncertainty limit of 1%. One can note that the uncertainty of the results which correspond to high pressure data from K-lab flow test is significantly lower than for CMR flow loop, where the pressure was significantly lower. This is due to the better quality of the data obtained at high pressure testing because of a better mixing and possibly more homogeneous flow.

For a bubbly flow regime the size of a typical bubble is normally defined by turbulent forces, which act to break the gas bubbles into smaller ones, prevent their coalescence and disperse them into continuous liquid phase [8]. The rate of turbulence is defined, amongst others, by liquid velocity, which will be different at different pressures. At higher pressure the gas density is increased, which decreases its buoyancy and hence the relative velocity with liquid, i.e. slip. So even if the superficial velocities are equal (i.e. volumetric flow rates), the liquid velocity at no-slip conditions will be higher than it is in the flow with slip, resulting in a higher turbulence level and better mixing.

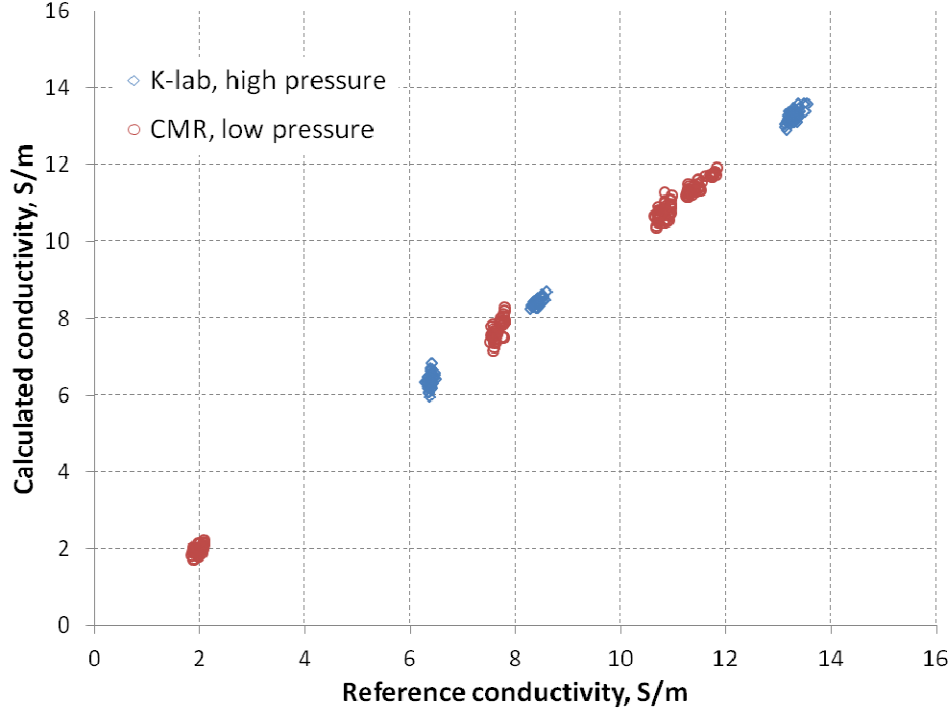


Figure 8. Microwave salinity sensor performance: Calculated conductivity vs. reference conductivity at multiphase flow loop.

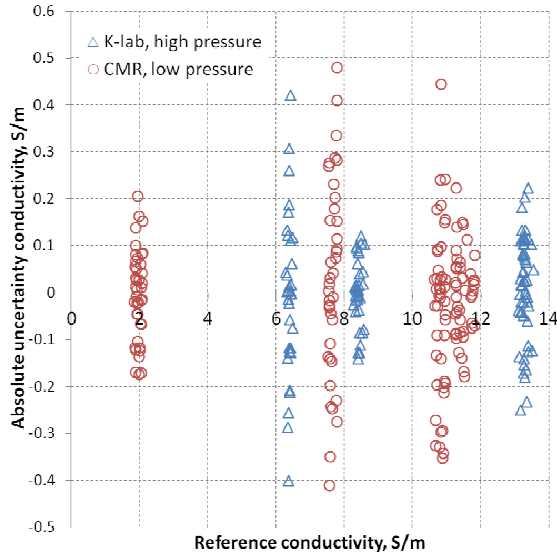


Figure 9. Absolute uncertainty in conductivity vs. reference conductivity.

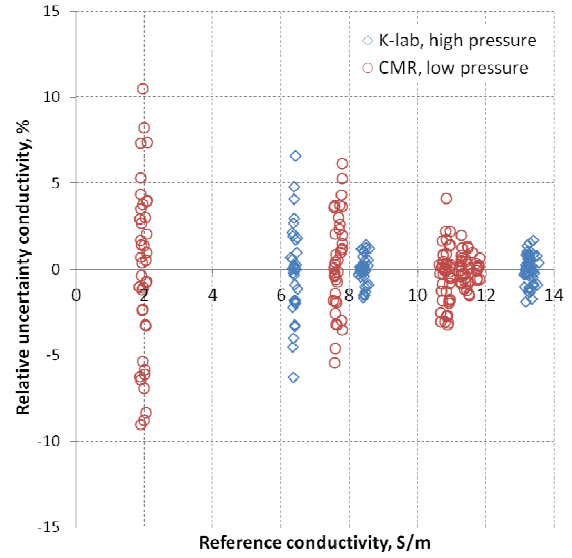


Figure 10. Relative uncertainty in conductivity vs. reference conductivity.

The effect of flow homogeneity is also illustrated in Figure 11, where the absolute uncertainty is plotted against reference GVF. One can note that the best performance is achieved at two-phase conditions (i.e. GVF=0%) and gradually deteriorates with the increase in GVF. This is caused by the increased heterogeneity of the flow due to presence of gas, which was discussed in section 3 of the paper.

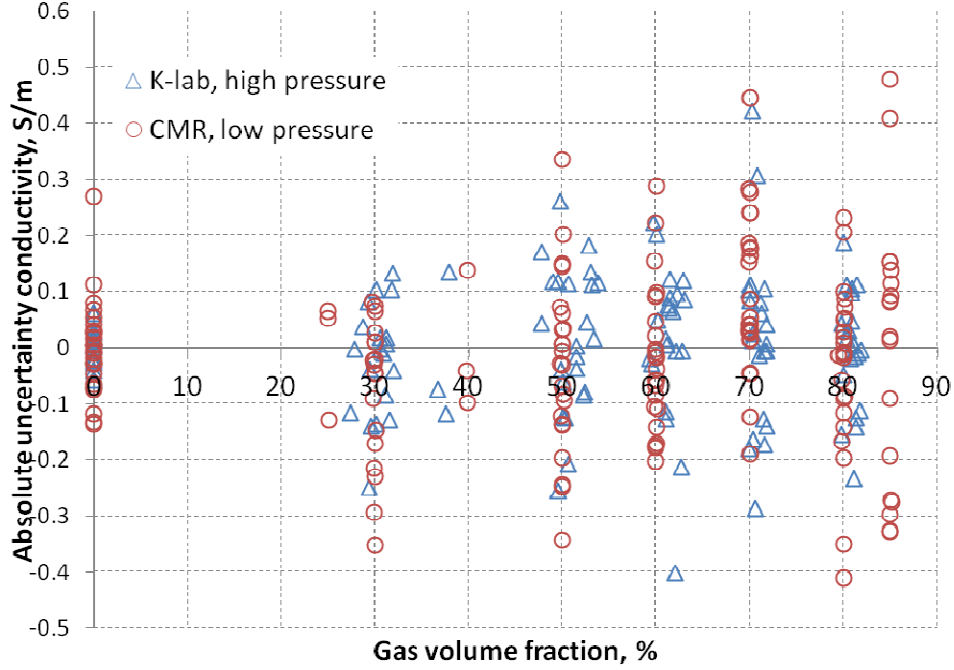


Figure 11. Microwave salinity sensor performance: Absolute uncertainty in conductivity for a tested GVF range.

6. Further development

The development work for the microwave salinity sensor is summarised and it is ready to be released as a fully qualified product. The ongoing development is focused on extending the range in terms of the amount of gas the sensor can handle while still delivering an accurate value of conductivity. As it has been demonstrated in this paper, the new sensor is capable to measure salinity in the range up to 90% GVF (which roughly corresponds to the transition from multiphase to wet gas flow). It has been observed during internal testing that it is most likely to extend its operating range higher in GVF. Such a sensor, which is capable of measuring in a higher end of multiphase flow range, will inevitably have a lower sensitivity to smaller amounts of water, which is specific to such flow conditions. This may introduce the need of considering actual flow conditions and analysis of the placement of the sensor within the body of the multiphase meter. Similar type of analysis to identify the optimal location of the ceramic salinity sensor has been performed in [3].

7. Summary and conclusions

The paper has introduced the microwave salinity sensor, which is capable of measuring water conductivity in multiphase gas/liquid flows over a wide range of flow conditions. The sensor has high sensitivity to salinity and, despite the challenges generic to multiphase flow, it is capable of measuring the conductivity of the water phase. The sensor is based on a two-parameter measurement, the differential attenuation and the differential phase

respectively, which together with information on the local flow regime, unambiguously provides conductivity of the water phase.

The sensor has been tested in low and high pressure flow loops. The test results show that the expected absolute uncertainty of conductivity measurement is 0.5 S/m with the lower relative uncertainty limit of 1%. The sensor has been tested within a conductivity range of 2-14 S/m through a test envelop which includes GVF 0-90%, water-liquid ratios 60-100%, pressures 5-125 Bar and temperatures 15-60°C.

9. References

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