An innovative salinity tracking device for Multiphase and Wet Gas Meter for any GVF and WLR

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1 INTRODUCTION

In the multiphase metering business, there is an increasing market need to monitor changes in the produced water salinity - taking place due to formation water breakthrough and/or water injection, or commingled oil-gas production, posing challenges to some multiphase flow meters with technologies which are more prone to salinity change than others.

Nucleonic fraction measurement has weak sensitivity to salinity change specifically when the WLR is below 30%. Meanwhile there are some needs of salinity tracking for watery wells to improve water cut measurement and flow rate performance in some limited and specific cases.

Extensive experimental testing carried out in 2002 and redesign and re-evaluation for current topside market have demonstrated that microwave sensors, based on open coaxial probe operating in the GHz-range, are able to detect rapidly early-water production and track salinity changes by measuring electrical conductivity of the water contained in a flowing mixture of oil-gas-water fluid.

This paper presents the results of this innovative Topside Conductivity Probe deployed and tested in very controlled flowloop facilities over a wide range of multiphase and wet gas flow conditions at different salinities.

The performance is stated in terms of online brine conductivity and salinity detection accuracy. The technical part of the paper will explain that the innovation comes from a new way to process the simultaneously measured conductivity and the permittivity data of multiphase-flow mixture in the vicinity/path of the sensing probe. The interpretation of unique combination of both measurements allows the sensor to work even in what is called oil continuous phase and presents a breakthrough in the salinity monitoring business by allowing to detect the first water droplet production when the well was only producing hydrocarbon (liquid and gas) earlier. Additionally, the measurement is enhanced by a unique environmental correction (ambient temperature change, electronic drift, and other...) and a way to compensate it for this fluctuation.

2 Vx TECHNOLOGY

The Vx Technology is the simplest multiphase flow meter (MPFM) combination on the market and is composed of a Venturi section and a fraction meter based on multi-energy gamma-ray source with a dedicated detector on the opposite side of the pipe. Each element has a specific role in the flow rate calculations process and all measurements are taken at the throat of the Venturi (the smallest section of the pipe, Fig.1).
2.1 The True Problem about Salinity Measurement versus Vx technology

The Vx technology robustness in the nucleonic fraction measurement is based on the weak sensitivity to salinity change specifically when the WLR is below 30-50%. Fig.2 shows the effect of salinity change on the WLR measurement without applying any salinity correction.

The strong argument about the robustness of the fraction measurement is nowadays balanced by some specific needs. Schlumberger has been looking into how to handle such situation and what have been the real market needs since 2002. It came out that the interest
was to detect the first droplets of water in wet gas conditions (e.g. for meeting subsea flow-assurance needs). This poses a measurement challenge when the flow is essentially hydrocarbon (gas). Additionally, the monitoring of salinity change could have some interests for the need of tracking for formation/injection water breakthrough in wells, or cleanup and improving water cut measurement and flow rate performance.

3 SALINITY MEASUREMENT & THE WAY TO ADDRESS IT

3.1 Background Experience

To be very sensitive to the presence of water, changes in water fraction and in water salinity it is then necessary to use electromagnetic measurement in the GHz (microwave) range. Xie and Pinguet [1] have shown the impact of salinity change with such technique of measurement and then the difficulty to guarantee accurate WLR. On the other hand, electromagnetic sensing could be used as a complementary method to the standard Vx meter to provide correction to the Vx technology, if the salinity change is not detectable with the Vx technology but can affect the measurement quality with the standard Vx data processing.

Schlumberger has been patenting in the measurement methods based on electromagnetism since the early days of the company and then has constantly been using it for the downhole tools. The main issue for multiphase flow measurement at surface (seabed or topside) is to find an adequate location for this measurement to be sensitive to the presence of water in any conditions (very high GVF >95%, low WLR range in the oil continuous phase, and capture the first droplet of water co-produced from oil or gas well). The key element is then to position at the right place for this additional sensor. It is also necessary to be cost effective and be capable of either providing a standalone solution or an add-on retrofittable to the multiphase flowmeter. Schlumberger, as early as 1996, has looked at few solutions in multiphase domain and took several patents.

All main multiphase flowmeter on the market today use a blind tee for several reasons and the main one to be independent of the upstream flow configuration and condition the flow to achieve high accuracy measurement. It was also demonstrated by E. Vethe et al. [2] that the blind tee is a relevant place for fluid sampling. Videos and CFD were used to position carefully a sampling device taking representative liquid and gas samples from a multiphase flow. It was naturally the relevant place to focus a bit more in details on the possibility to set additional sensors. The pictures in Fig.3 show clearly that even with extremely high GVF in average there is a liquid-rich region present either in the bottom a blind tee or at the end of the blind tee.

![Fig. 3 – Blind Tee: A compulsory element of the 3-phase Multiphase and Wet gas Meter](image)

One of the main discovery of the extensive study of the blind tee functionality was to identify places were high liquid enrichment is present for any GVF. The figure 4 below shows the
liquid enrichment efficiency versus GVF - a logarithmic scale has been selected on the y-axis. At low GVF, more than 60% of liquid are added inside a sampling bottle versus the line conditions, and this goes above 5,000% at extremely high GVF (98%). This highlights that the design to collect the liquid is extremely robust and works on the full range of GVF.

Fig. 4 – Results showing the performance of collecting enriched liquid sample at different GVF

Focusing on the liquid sample and looking at the representativeness of the WLR within the limit given show that most of the data are well within a standard deviation of 2.5% (Fig.5). The uncertainty on the WLR is independent of the GVF. This means it is possible to verify the performance with a relevant WLR/BSW reference from this sample.

Fig. 5 – Subset of data showing the comparison of the local WLR measurement versus global WLR measurement (also called Reference)
3.2 A local measurement of the permittivity and conductivity

To make a differentiation between condensed and formation water (Water Breakthrough) requires a technique of measurement capable of having a large contrast between water and hydrocarbon. The use of the electromagnetic measurement is based on the large contrast between water and hydrocarbon (gas or liquid) from permittivity and conductivity point of view.

\[
\begin{align*}
\varepsilon_r &= 81-4k; & \varepsilon_{r,\text{water}} &= 80-26 \text{ at} \; 25^\circ\text{C}; \\
\varepsilon_r &= 2-2.5; & \varepsilon_{r,\text{oil}} &= 0 \text{ at} \; 25^\circ\text{C}; \\
\varepsilon_r &= 1; & \varepsilon_{r,\text{gas}} &= 0.96 \text{ at} \; 25^\circ\text{C}.
\end{align*}
\]

The main drivers for the development of the brine conductivity measurement is to measure in terms of a complex permittivity in GHz range which leads to mixture conductivity and permittivity and their ratio (indicative of flow-mixture loss factor), then assuming a given salt composition it will provide an equivalent salinity.

The right way to progress in the detection of the water is then not to try to measure the complex permittivity or attenuation of the electromagnetic wave over the full pipe cross section. Indeed, going in this direction of a global measurement does not help to solve the problem when there is a large amount of gas present with tiny amount of liquid; the resulting complex permittivity output is still very low due to the presence essentially of gas, leading to an improper complex permittivity measurement of the liquid and its water-phase conductivity. Again, it is the position of the probe in a relevant place which is instrumental to the success in such conditions.

The measurement concept with electromagnetism put in practical industrial application is based on a patent established more than 10 years ago and on the use of reflection signal on an open-ended coaxial probe of an electromagnetic wave.

There are several advantages to this system, first it is a compact solution and then it is well known in the literature. The specially designed high-pressure and high-temperature withstanding probe is compact and has a diameter of less than 10 mm. The front aperture of the probe will be in contact with and face the incoming flow, and has an investigation depth of a few millimeters ahead of the probe (Fig. 6).

![Fig. 6 - Electromagnetic Probe for TOPSIDE Solution (left side) and some dimensions with a probe slightly inside the main pipe with a depth of investigation of a few mm and the concept of measurement by reflection (right side)](image)

The electrical field created by the coaxial probe will be modified by any droplet of oil and water and will create a reflected electromagnetic wave that contain the electrical impedance (hence complex permittivity) information about the type of fluids present at that time in front of the probe. Measuring the incident wave and the reflected one by using a thermally stablized...
microwave electronics circuit it is possible to calculate their ratio - the complex reflection coefficient. The flow-mixture complex permittivity (and their ratio or loss factor) used to determine brine electrical conductivity (salinity) can be derived from the measured reflection coefficient.

A classical calculation based on a a bilinear model (relating complex permittivity and reflection coefficient) is made with some additional factory calibration with few known fluids, the complex permittivity can be calculated under the following form:

\[ \varepsilon_m = \varepsilon' + i\varepsilon'' \]

\( \varepsilon' \): The real part is known as the permittivity (or to simplify here to a dielectric constant)

\( \varepsilon'' \): The imaginary part is largely proportional to the electrical conductivity given the microwave measurement frequency

3.3 Local Measurement & the Innovative Data Processing

Based on the above explanation, it is then possible to produce in real-time a signal to spot the water presence inside the flow. This is presented on the Fig. 7 versus time (30 seconds recording), where the GVF is equal to 99.5% or only 0.5% of liquid, with a WLR \( \sim \) 25% and the Water Volume fraction (WVF) is equal to 0.125\%=1250ppm. The spikes seen on both graphs represent the water passing in the vicinity of the probe or hitting the probe.

![Fig. 7](image_url)

**Fig. 7** – Permittivity (left) and Conductivity (right) Measurement versus time (30 seconds) with GVF=99.5%, WVF=1250ppm, and WLR=25%

The same recording is presented with now WVF=0.0337\%=337ppm but a WLR\~\ 34% and a GVF=99.9%. It can be noted that more droplets are present in this flow now.

![Fig. 8](image_url)

**Fig. 8** – Permittivity (left) and Conductivity (right) Measurement versus time (30 seconds) with GVF=99.9%, WVF=337ppm, and WLR=33.7%
The innovative way to handle the microwave measurement data is to look at them not versus time but in terms of cross-plotting conductivity vs. permittivity (see Fig. 9). The ratio of mixture conductivity over permittivity (indicative of the loss factor) is constant for a fixed salinity (at a fixed temperature). Through the use of an interpretation algorithmic method not explained here it is capable of providing the ratio of water conductivity over water permittivity (i.e. 100% of water) and then access to the salinity, over a wide range of multiphase-flow GVFs and WLRs.

The originality of the solution is due to the local measurement at the blind-tee location of the fluids close to the probe aperture and the fact that the system is not looking into the entire flow but a subset which is “full” of liquid-rich fluids. Even though the pipe-averaged liquid holdup is probably very low (and with oil being the continuous phase), the local liquid (water) holdup is much higher with less presence of the gas phase.

![Typical Trace with Gas & Oil Slug](image)

**Fig. 9** – Data processing to get access to the salinity in real-time by looking into cross-plot of conductivity and permittivity (upper), and below showing the variation of mixture conductivity recorded versus time.

### 3.4 Local Measurement & Blind Tee

The last need to solve our initial problem was to find a way to see the first droplets. As we know in Wet gas conditions the Froude number is usually high and then the liquid droplets are most of the time suspended in the gas flow, if this is not the case then by gravity the liquid will be in the bottom of the horizontal pipe and then the problem to handle is much easier based on the know-how from CFD and high speed flow-visualization camera video recording collected over the years about the blind tee effect.

The appropriate way for early water droplet detection is then to have the open-coaxial probe facing the incoming flow and set in a relevant place at the back-flange of the blind-tee inlet (Fig.10 right). Fig. 10 (left) shows the Topside Conductivity Probe module upgraded on a Vx Spectra meter with its own acquisition system (modular in the final offering to customers).
4 SALINITY MEASUREMENT AND THE TRUE PROBLEM

4.1 Salinity measurement in stable flow conditions

The variation in the water-rich multiphase-flow mixture complex-permittivity ratio is dominated by the water-conductivity change. This is presented, Fig. 11, based on the DNV-GL flow loop test results as the cross-plot of the measured (time-averaged) mixture-conductivity vs mixture-conductivity. We can observe a very stable mixture conductivity-to-permittivity ratio for each fixed brine salinity (brine conductivity), at least down to conductivity of 0.5 S/m or permittivity of 8. This is the key to obtain robust brine-conductivity/salinity estimate even in bulk oil continuous phase or reaching wet-gas phase flow conditions.

Fig. 11 – Cross-plot of time-averaged (between 10 to 25 minutes) mixture-conductivity vs mixture-permittivity for all tested three salinities at DNV-GL.

The typical GVF-WLR phase diagram is presented in Fig. 12 with the same color coding as those shown on the Fig. 11 to give an idea about the flow conditions.
In Fig. 13, the measured salinities are plotted vs. the average WLR, superimposed with the calculated (for Vx) brine-salinity error bands of equivalent ±2%-WLR-error. We can observe that there is a decreasing sensitivity, with decreasing WLR, of the Vx WLR measurement accuracy to the changes in the (NaCl) brine salinity but way within 2% target.

Fig. 13 – The time-average of brine salinity vs WLR for all 3 tested salinities, with calculated (for Vx) brine-salinity error bands shown of equivalent ±2%-WLR-error (absolute).
4.2 Salinity measurement in dynamic change conditions

The demonstration of the salinity tracking during the change of salinity was the next step to ensure the entire solution was satisfactory in dealing with dynamic change. Among the multiple tests made on flowloops, it is presented in Fig. 14 the tracking of the water salinity change from fresh water to salinity close to 6kppm. It can be seen clearly that the measurement is close to 0 most of the time, then the injection of salty water is made, this is done when the flowloop is still running and then a breakthrough of high salinity is detected before the mix of the fresh and salty water is stabilizing through recirculation inside the flowloop and stabilizing around 6kppm.

![Fig. 14 – CEESI salinity change from 0 to 6kppm over few minutes.](image)

Another recording with a salinity change this time from 6kppm, to 27kppm and to 55kppm. The two steps in salinity introduction can be seen in Fig. 15 and the decay from the peak value on the last part is when the entire flowloop and all section with still fresh water trapped inside have been opened to mix entirely the water to a stable salinity.

![Fig. 15 – CEESI salinity change from 6 to 30 to 55kppm over few minutes.](image)
5 CONCLUSION

The microwave open-coaxial probe used to provide brine conductivity is based on the simultaneously measurement of the mixture conductivity and the (dielectric) permittivity of multiphase-flow mixture in the vicinity of probe’s front aperture, by measuring the amplitude-attenuation and phase-shift of reflected microwave signals. The probe is mounted in a well-defined place inside a blind-tee to ensure the early water detection (first droplet of water) and with a place collecting enough liquid even when the GVF is extremely high (>99%)

From the multiples flow loop tests, we can conclude that stable and accurate multiphase-flow fluid property measurements have been achieved to meet brine conductivity (salinity) accuracy requirement. The brine conductivity is quantitatively measured within ±5% (or ±0.5 S/m) for WLR>~25%, GVF up to 99%. The corresponding brine-salinity calculation is also within ±5%.

A mix of quantitative and qualitative measurement for lower WLR (as low as 2%) was achievable but as indicated earlier in this low WLR range the nucleonic fraction meter is weakly sensitive to salinity variation and provide good performance already as a standalone solution.

The use of a unique environmental (thermal-drift) correction based on a stabilised measurement is an enabler of high accuracy. In this challenging condition of GVF above 95% and WLR in the oil continuous phase (WLR <40%) the Vx technology is proposing a unique solution. A careful evaluation of the performance is ongoing to state the right value at such very low WLR.

The brine conductivity probe solution is proposed either as a standalone solution or for enabling higher accuracy Vx WLR measurement by using Conductivity probe salinity-tracking input to the Vx technology.

6 REFERENCES
