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Paper 4.1

New Compact Wet Gas Meter Based on a Microwave Water Detection Technique and Differential Pressure Flow Measurement

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1 INTRODUCTION

Future field developments will include wet gas or gas-condensate fields with a very high GVF. In these cases, a test separator for well testing is often not a possible option and inline flow instruments will be requisite (see e.g. [1]). The use of inline wet gas meters will be important to the field operators for well testing, continuous reservoir monitoring and production optimisation, allocation and flow assurance.

Fig. 1 The Mikkel subsea wet gas meter

The gas flow rate measurement is obviously a main focus of the wet gas metering technology because the gas value of the stream is dominating. This is however not the complete picture. In some gas-condensate fields, the value of the condensate production may be significant. It is moreover important to have a measure of the liquid components in the gas (condensate/water) for instrumental reasons, to improve the flow rate measurement accuracy.

The water detection capability of wet gas meters will be particularly important because, for some of the installations, even small amounts of formation water will be critical. Such fields are characterized by long-distance multiphase pipelines connecting to the process area. Moreover, the formation water production profiles for gas-condensate fields are notoriously difficult to predict. Irrespective of this fact, design premises need to be established for the development of such fields. When they are developed, there will be built-in limitations with respect to operational formation water tolerances for various parts of the production systems. The need for a wet gas meter that can detect small amounts of water in the wet gas gas/condensate stream is obvious in such applications.

As an example, Statoil is currently developing two subsea fields where the selected corrosion mitigation philosophy totally depends on the use of a wet gas meter technology that includes the detection of formation water. The Snøhvit field (GVF > 99%) is a subsea-to-beach development offshore northern Norway, whereas Mikkel (GVF 91 – 98%) is a small satellite-to-satellite field offshore mid Norway.

TotalFinaElf has also, on a general basis, identified the inline wet gas metering as a key point in many future field developments. In particular, deeper gas reserves in subsea fields far away from existing facilities has given rise to the conception of longer subsea tieback in which an increasing number of wells or even fields are connected to a single flow-line. Such applications will benefit from the use of wet gas meter installed on each wellhead of a subsea manifold.

Commercial multiphase meters, covering low to moderately high gas fraction, have been successfully implemented in many production sites worldwide. Meters for the dry gas flow measurement are also more or less standard off-the-shelf products. The experience, however, is that the traditional multiphase meters do not handle GVFs over 90 to 95%, as above 95% GVF, none of today's multiphase meters can meet the requirements needed.

Motivated by the demands for reliable wet gas meters with water detection, a development program was initiated by Roxar Flow Measurement (RFM) by mid 2000 to develop such a meter and to try to adapt it to the operators' real needs. The development program, run by RFM, Statoil, and TotalFinaElf, has been goal-oriented with a period of only two years from the basic ideas was formed until delivery of the first commercial unit.

The first commercial meter, a compact subsea version, has now been produced for installation in Statoil's Mikkel field (Fig. 1). The sensor is a 5" subsea version that is 650mm from flange to flange.

The measurement concept is based on microwave technology in combination with a differential pressure flow meter and PVT calculations. Performance tests have demonstrated a water detection accuracy of size $\pm0,1\text{-}0.2\%_{vol}$ with a sensitivity better than $\pm0,01\%_{vol}$ and a mass flow measurement accuracy of size $3\text{-}5\%_{rel}$.

2 FIELD APPLICATIONS AND METER REQUIREMENTS

2.1 Statoil

For Statoil's concern, the needs and requirements to wet gas metering technology is directly related to the Snøhvit and Mikkel fields. In both cases, the carbon steel pipelines will be protected initially by a combination of a film forming inhibitor and injection of a pH-stabilizing agent. However, once the formation water production exceeds a predefined limit, the pH stabilization needs to be terminated to avoid excessive scale precipitation in the pipeline. The need for metering in these to cases can be seen as typical for many of Statoil's future developments. An extensive test program has now been started to ensure that the chosen technology can cope with the needs at both Snøhvit and Mikkel.

2.1.1 Snøhvit

Snøhvit is a wet gas field under development in the Barents Sea with subsea production installations, a pipeline to shore, and a gas liquefaction plant in the northern Norway.
Including the Albatross and Askeladd discoveries as well as Snøhvit, this project will be the first offshore development in the Barents Sea. It also ranks as the first project in Europe based on the export of liquefied natural gas (LNG).

The untreated well stream will be piped about 160 kilometres from the field to a treatment plant at Melkøya outside Hammerfest in Finnmark County. After water, condensate (light oil) and carbon dioxide have been separated from the gas, the carbon dioxide will be piped out to sea and injected in a sub-surface formation. The lean gas will be liquefied for transport to customers, using LNG carriers. To be pursued in stages, the development involves a total of 21 production wells and 1 carbon dioxide injector in subsea templates standing in some 320 metres of water.

In the Snøhvit case a high regularity in combination with low uncertainty in the subsea metering are essential factors for having a successful field development. The consequence of not using wet gas meters would be unacceptably high from an economical point of view. Over-injection of chemicals (hydrate inhibitors and others), as well as loss of control of the long distance multiphase pipeline system would be the result. The alternative to the use of wet gas meters at Snøhvit would be to use the valve characteristics for the choke valve in combination with pressure and temperature data.

The uncertainty associated with this approach is substantially higher. In addition, a larger flexibility would be required in other parts of the system, both offshore and onshore. In addition to the increased investment and operational costs, there is a demand in the Snøhvit case for a regularity of more than 98%. This would be impossible to meet, if no wet gas meters were available.

The philosophy of using wet gas meters is that immediate correction can be effectuated as the water is detected. Without the wet gas meters, there would have been a lag of 3 days from the

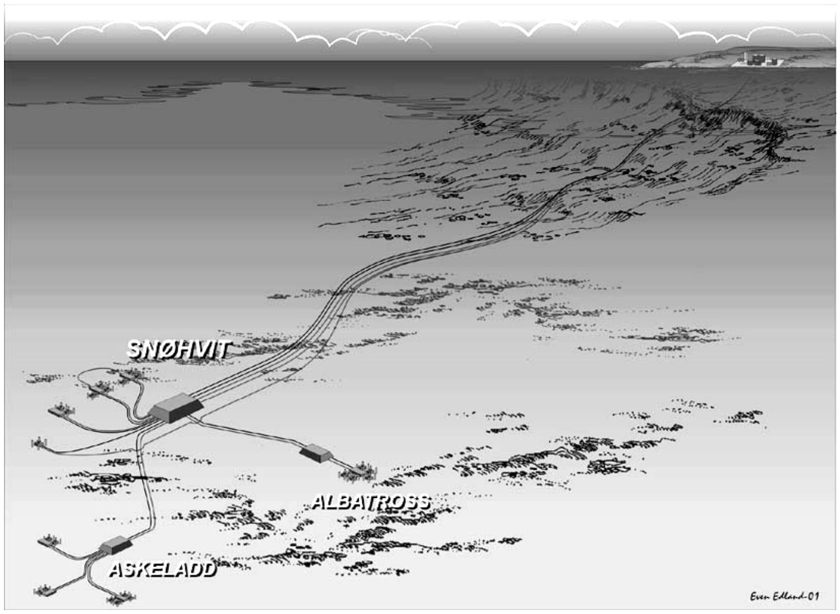

Fig. 2 Statoil – Snøhvit field

start of increased water production until it could be detected onshore. Build up of large deposits of salt in the pipeline, would have been the result.

As well as increasing the regularity, lowering the chemical injection, cutting investments and operational costs, the wet gas meters will lead to an improved reservoir management. Well testing in a traditional way is not possible at Snøhvit, and the wet gas meters will give a better reservoir control than the use of traditional well performance profiles.

To meet the overall goal for the production plant at Melkøya as well as the subsea system offshore, it is an absolute demand that the wet gas meters have a high regularity,

Snøhvit target:

- **Range:**
  GVF: 99 – 100%
  WLR: Low (close wells with increasing WLR)

- **Sensitivity WVF:**
  ± 0.01 $\%_{vol}$
  Formation water production changes: 1 m^3/day pr. well.
- **Uncertainty WVF:**
  ± 0.1 $\%_{vol}$
- **Total mass flow rate:**
  ± $3\%_{rel}$

2.2 Mikkel

Mikkel is a gas-condensate field located 35 kilometres south of the Midgard field. The latter is a subsea installation with multiphase pipeline connection to the Åsgard B platform. The Mikkel subsea installation will contain two wellhead frames with two producers on each frame.

The Mikkel gas goes with the production from the Midgard field to Åsgard B, then through the Åsgard Transport trunk line to Statoil's Kårstø treatment plant north of Stavanger and finally on to continental Europe. The Mikkel fluid will be mixed with the production at Midgard before arriving at Åsgard B. At Åsgard B, the total production from both Mikkel and Midgard is measured.

At the receiving process plant at Åsgard B, metering of water is essential. The regeneration plant for Glycol at Åsgard B has an upper limit of approximately 63 m3/d from Mikkel. With no

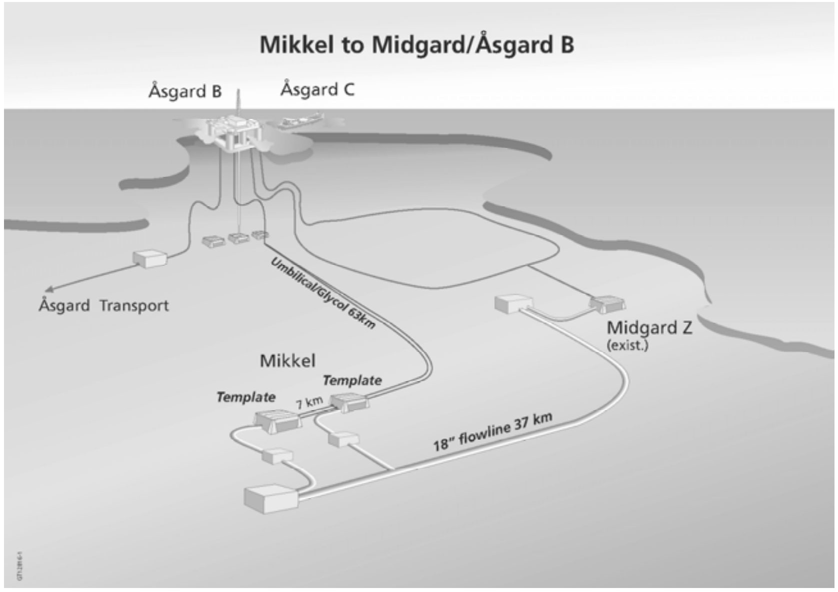

Fig. 3 Statoil - Mikkel field

water measurement at the wellhead, overflowing of the regeneration plant may be the result. The latter would be destructive since the regeneration plant at Åsgard will most likely not be expanded due to the high cost.

In addition, the reservoir control will be limited with respect to water break through and capacity limitations. Midgard has no metering of wet gas or water. The only way to find the water producing well, is by shutting in wells one at a time. This decreases the regularity of both Mikkel and Midgard, and will become an expensive operation to perform, with large losses of production for both fields.

Mikkel target:

- **Range:**
  GVF: 91.5 – 100%
  WLR: 0 – 100%
- **Uncertainty WVF:**
  GVF 99-100%: ± 0.1 $\%_{vol}$
  GVF 95-99%: ± 0.2 $\%_{vol}$ (oil continuous flow at well head)
  GVF 90-95%: ± 0.3 $\%_{vol}$ (oil continuous flow at well head)
- **Total mass flow rate:**
  ± 3-5$\%_{rel}$

2.3 TotalFinaElf

TotalFinaElf has identified the development of a reliable and cost effective wet gas metering technology as a key element in many future field applications including unmanned and subsea installations. That includes wet gas fields with a GVF above 99$\%_{vol}$ as well as gas-condensate fields with a GVF down to 90$\%_{vol}$.

The meter will potentially be used for gas and condensate allocation, reservoir and well monitoring and detection of water production in order to optimise methanol inhibition and prevent expensive blockages. The requested information is gas flow, water content, and condensate content. It would also be advantageous with a measurement of water salinity (conductivity) to be able to identify formation water break-through.

TotalFinaElf has during the last years [1] been studying and developing adequate venturi models to be used in wet gas applications. These studies have shown that the flow morphology (droplet size, slip between phases, degree of liquid entrainment in the gas) has an effect on the differential pressure flow meters that should be taken into account. The ability to measure the liquid content and water cut will hence be essential factors for a high accuracy gas flow measurement.

General meter design target:

- Measurement of all three phases without separation.
- No moving parts.
- Subsea as well as topside versions should be available.
- Robustness with respect to flow property variations (H_2S, velocity, sand production and erosion, deposits, wax).
- Cost effective design.

General specification targets:

- **Range:**
  - Wet gas field GVF: 99 - 100%
  - Gas-condensate field GVF: 90 -100%
  - WLR range: 0 - 100%
- **WVF accuracy:**
  - Wet gas fields: ± 0.02 – 0.05 $\%_{vol}$
- **Gas flow accuracy:**
  - Well testing / monitoring: ± 5 – 10 $\%_{rel}$
  - Allocation: ±1.5 - $5\%_{rel}$
- **Liquid flow accuracy:**
  Typically ± 5 - 20 $\%_{rel}$, depending on applications

3 THE TECHNOLOGY

The wet gas metering technology developed is described in the following, the measurement concept being illustrated in Fig. 4.

The WGM detects the water content based on microwave technology and flow rates using a venturi or V-Cone differential pressure device. The split between gas and condensate is found using PVT calculations.

Two solutions are currently available, a V-Cone (Fig. 5) and a Venturi based version (Fig. 6). The V-Cone version is the most compact WGM solution that is integrable in most subsea modules and is used for Mikkel. It has an advantageous water fraction technology that is an integrated part of the flow element. The venturi solution is more space consuming but has the advantage that the geometry is less intrusive and that the need for flow meter calibration is minimized.

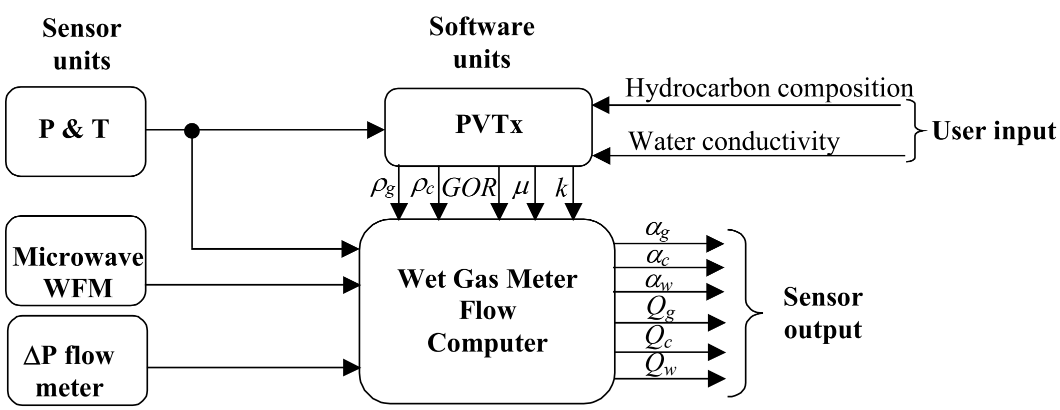

Fig. 4 WGM measurement concept

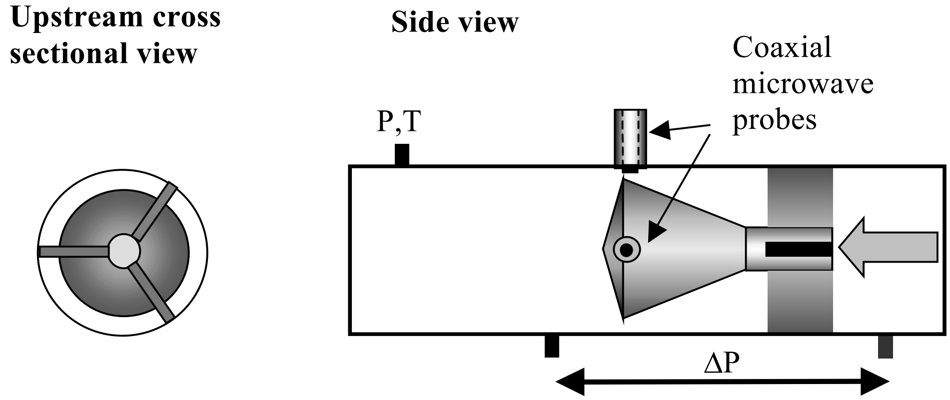

Fig. 5 V-Cone based Wet Gas Meter

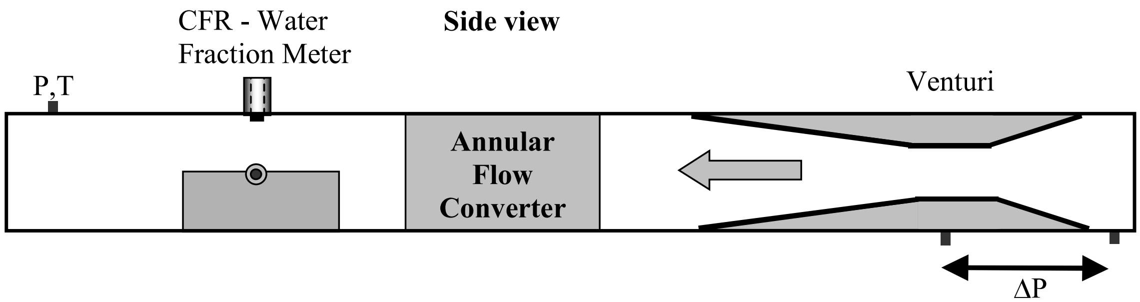

Fig. 6 Venturi based Wet Gas Meter

3.1 Microwave based Water Fraction Meter

The Water Fraction Meters (WFM) detect the resonant frequency in a microwave resonance cavity. The resonant frequency depends on the dielectric properties of the fluid mixture that is instantaneously present in the cavity. The dielectric properties of the mixture are functions of the composition, i.e. the fluid fractions.

The permittivity of water (~60 - 200) is much higher than that of gas (~1) or oil / condensate (~2). The dielectric properties of the wet gas mixture are consequently very sensitive to the water content and the WCM is basically used to deduce the water volume fraction.

The mixture permittivity, ε_{mix} is generally related to the measured resonant frequency, f_r, by the formula [2]:

$$\varepsilon_{mix} = \left(\frac{f_{vac}}{f_r} \right)^2 \qquad (1)$$

where f_{vac} is the vacuum frequency. The measured mixture permittivity can subsequently be used to deduce the individual volume fractions of the constituting materials (water, gas, condensate) using certain mixing formulas and the known permittivity of each of the constituents. The RFM meters are based on the Brüggeman [3] type of formula:

$$\alpha_i = 1 - \frac{\varepsilon_i - \varepsilon_{mix}}{\varepsilon_i - \varepsilon_h} \cdot \left(\frac{\varepsilon_h}{\varepsilon_{mix}} \right)^{1/3} \qquad (2)$$

where ε_h is the permittivity of the continuous host material (gas in our case), ε_i is the permittivity of the inclusion material (condensate or water) and α_i is the volume fraction of the inclusion material. The measured water fraction is compensated for the presence of water vapour and the appearance of slip in the WFM sensor.

The Cylindrical Fin Resonator (CFR) water fraction meter, used in the venturi based WGM, utilises the same principles as the RFM WaterCut sensors. The CFR sensor is based on the fact that the microwave cut-off frequency of a pipe with an axially oriented fin extending to the centre of the pipe is substantially lower than that of the plain pipe. The electromagnetic standing waves are hence confined to the region that contains the fin (see [4] Ch. 6 for details). A so-called annular flow converter (AFC) is employed to entrain the liquid film into the gas core in the case of an annular flow regime.

The idea of using a V-Cone as a combined dp flow meter and microwave resonator was conceived as part of the wet gas meter development program reported in this paper and a patent is now pending for this invention [5]. The electromagnetic behaviour of the V-Cone sensor can be viewed as a ¼ wavelength coaxial resonator. where the electromagnetic energy is confined in the microwave cavity as defined by the V-Cone length. This structure has an advantageous electromagnetic field distribution (Fig. 7) that makes is well suited for water fraction detection in a wet gas stream.

- In the axial direction, the field has its maximum at the cone edge were the gas velocity is highest. The water content will hence be measured at this location.
- The field is uniformly distributed along the circumference of the gap, making the sensor less flow regime dependent.
- Computer simulations of electromagnetic fields using the FEM method as well as measurements have shown a frequency response with a clean and single resonance peak in the actual frequency range (Fig. 8).

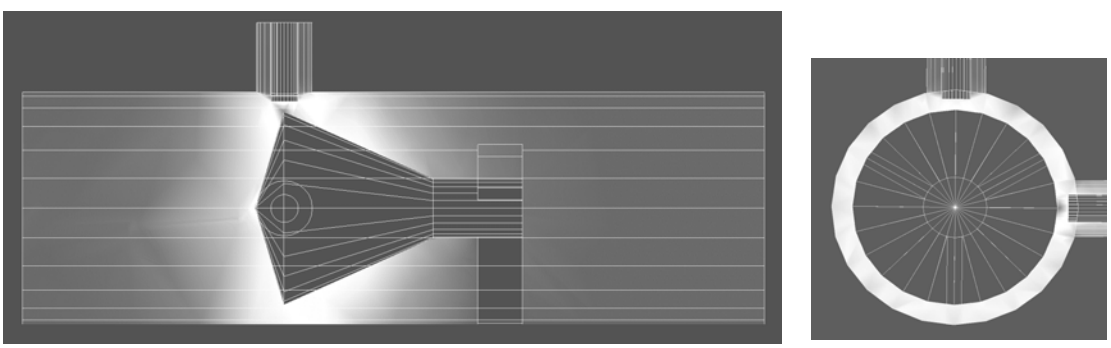

Fig. 7 Electromagnetic field distribution of V-Cone resonator

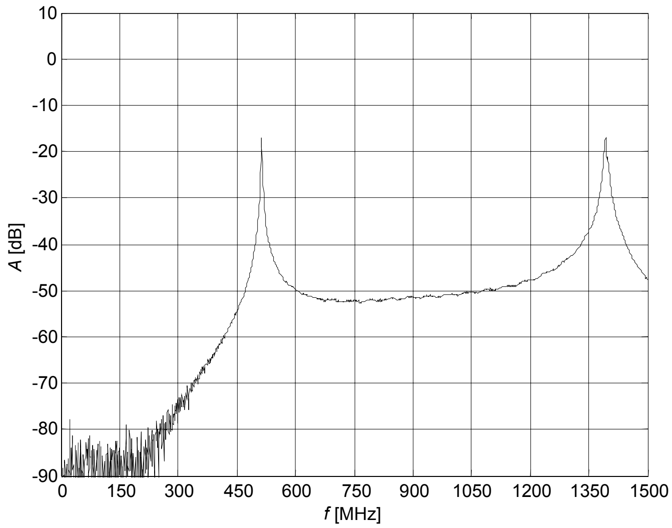

Fig. 8 Typical microwave response of V-Cone WFM.

3.2 Differential pressure Flow Meter

The individual flow rates are measured using a venturi or V-Cone differential pressure flow meter. The measured differential pressure basically depends on fluid density, composition and flow velocity. In the case of 2-phase wet gas flow, the gas rate is generally given by the following standard formula that applies for a venturi and for a V-Cone [6]:

$$Q_g = \frac{\pi D^2}{4}\frac{C_D \cdot y}{\Phi_G}\sqrt{\frac{2 \cdot \Delta P \cdot \rho_g}{\left(\beta^{-4} - 1\right)}}, \qquad (3)$$

where C_D is the gas discharge, y is the fluid expansibility and Φ_G is the 2-phase Lockhard Martinelli gas multiplier [7]. The gas multiplier is a function of the Lockhard Martinelli parameter, $\Phi_G = \Phi_G(X_{LM})$ were

$$X_{LM} \equiv \frac{1-\alpha_g}{\alpha_g}\sqrt{\frac{\rho_l}{\rho_g}}, \qquad (4)$$

Experimentally based correlation models define the gas multiplier function. Chisholm [6], Murdock [8], and de Leeuw [9] type of correlation models have been studied in the K-Lab flow test.

3.3 PVT Software

A PVT software package (Roxar PVTx) is integrated as part of the WGM software. Input to the PVT package is hydrocarbon composition and it is being used to:

Calculate the gas and condensate density

Calculate the actual Gas / Oil volume Ratio (GOR) at meter conditions. The calculated GOR is subsequently employed to discriminate between gas and oil / condensate and hence to deduce the condensate and gas fraction once the water fraction has been found using the WFM.

Convert from meter to alternate conditions (usually standard conditions)

3.4 Gamma Densitometer

The application of a gamma densitometer in the WGM is optional. It can be used to measure the fluid density and hence to estimate the condensate content of the wet gas. The gamma densitometer can be useful if one wants an indication of an unexpected change in the hydrocarbon composition.

The use of conventional gamma densitometer technology to deduce the liquid content of a wet gas stream will however suffer from a limited long-term accuracy because of its fundamental statistical character. In subsea applications, were recalibration is difficult, this is a particularly important limitation. The use of a conventional gamma densitometer for liquid detection will only be relevant in the case of gas-condensate fields with a moderately high GVF (<~ 99%).

The tests at K-Lab indicated that a resolution of size 2 kg/m^3 could be expected. For a typical case with a GVF of 95% and a gas density of 150 Bar, this resolution corresponds to a change of the condensate fraction of the order 1%$_{vol}$. The gamma densitometer can hence be used to indicate changes in the liquid content of the order 1%$_{vol}$,

4 K-LAB TEST

As part of the Wet Gas Meter development program, a performance test was carried out on prototype sensors at Statoil’s test facility, K-Lab, in the period Sept-Oct 2001.

The K-lab rig, used during the prototype testing, is an open loop where “fresh” fluids are being used continuously. This is an advantage, since it gives the best control of the reference fluids, not being affected by unwanted phase transitions or emulsifications in a separator system.

The gas used is unprocessed rich gas taken from the inlet to the Kårstø plant. Samples of the gas entering Kårstø is taken on a daily basis, and the gas composition is known with high accuracy. After pressure reduction, the gas is heated in a steam driven heater to the wanted temperature. The gas is measured with an orifice plate metering station, using AGA-8 calculation for the density. Downstream the gas reference metering station, water and condensate is being injected. Both injection liquids are pumped into the flow line using electrical driven piston pumps, and measured using Coriolis meters. Each fluid has its own metering station with a 1” and ¼” Coriolis sensor depending on the actual injection flow rate needed.

The test program consisted of about 150 experimental points with the following variations in flow parameters:

Temperature:	20 - 80^{o}C.
Pressure:	10 - 80 Bar
Gas flow rate:	400 - 3900 kg/h
Condensate flow rate:	0-2600 kg/h
Water flow rate:	0-2400 kg/h
GVF:	91.5-100%$_{vol.}$
WLR:	0-100%$_{vol}$
Water salinity:	0 – 7.5%$_{wt}$
Methanol test:	40/60% Water/Methanol solution used
MEG test:	40/60% Water/MEG solution used

4.1 Water Fraction Measurement

The WFMs demonstrated a good sensitivity to variations in the water content. The meters were able to detect variations in the water content with a sensitivity better than 0.01 %$_{vol}$. One example of the detection of water steps is shown in Fig. 9. In this case, the gas and condensate flow rates were held at a constant level while the water injection was turned off.

Note that this plot has an offset and gain error. Such errors can be reduced if the meter is calibrated inline. The important point, however, is that the WFMs are capable of detecting extremely small changes in the water content.

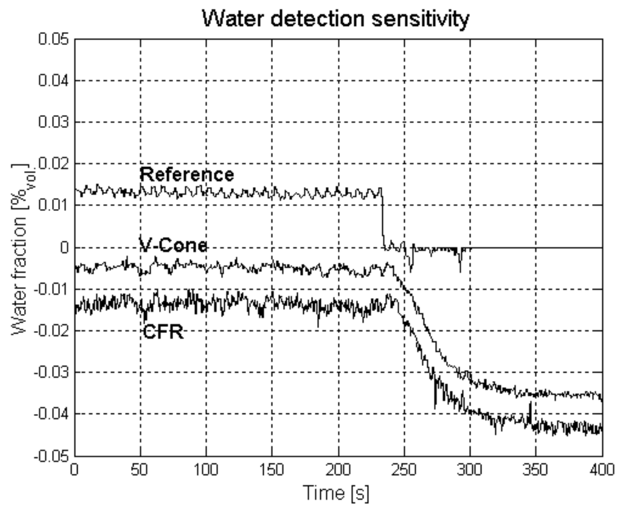

Fig. 9 Demonstration of water detection sensitivity where a step of size 0.013$\%_{vol}$ in the water content is easily detected.

One of the test series carried out at K-Lab, with a GVF larger than 98.5%, is shown in Fig. 10. In these experiments, the water detection accuracy was observed to be of size ±0.1 $\%_{vol}$ (90% conf.), which is in accordance with the targets defined by the operators (See Sec. 2). In a real application were one expects small variations of water content around a certain value, it will in principle be possible to improve the accuracy using a so-called inline calibration method. It means that the WFM is calibrated after being installed in the actual well. Inline calibration is possible if the water content of the well stream can be sampled.

A test series with a larger span in the GVF (91.5-99%) was also carried out. The results depended on whether the continuous host component of the liquid phase being water or condensate. In cases with a WLR <~ 50$\%_{vol}$ (condensate-continuous), the water fraction technique worked well with an accuracy of ±0.2 $\%_{vol}$. As the liquid phase turned into the water continuous phase, however, the water fraction was systematically overestimated and finally the meter failed. The latter effect is being caused by:

- In the case of water continuous droplets, the condensate is “hidden” inside water droplets. According to theoretical predictions, the permittivity of a water droplet containing oil as an inclusion will be close to that of water. Consequently, the water content will be overestimated.
- As the GVF decreases, an increasing amount of liquid will flow as a film along the pipe wall. When this liquid film is water-continuous it will finally flood and “short-circuit” the microwave antennas.

4.1.1 Special tests

Special tests were carried out to test the sensitivity of the water fraction meters to variations in the water salt content and to injection liquids like methanol or MEG.

The salt content test revealed that the sensitivity to variations in the water conductivity is in most cases low. According to the Brüggeman mixing theory, a typical value for the sensitivity of water fraction measurements to the errors in the water conductivity input is

$$\frac{\partial \alpha_w}{\partial \sigma} \sim 1.5 \cdot 10^{-5} \qquad (5)$$

which means that an error of 1mS/cm in the input conductivity will lead to an error of 0.0015$\%_{vol.}$ in the water fraction measurement. The experiments confirmed the theoretical predictions for low salinities (0.3 and 1.5 $\%_{wt}$) but revealed that the sensitivity was higher than expected in cases of very high salinity. (7.5$\%_{wt}$), probably caused by the non-Brüggeman wet gas mixing.

Two test series were also carried out to check the effect of methanol or MEG injection. Theoretically, such substances should be detected almost as water. This was confirmed by the K-Lab experiments when water was replaced by a 40/60 Methanol/water or MEG/water solution.

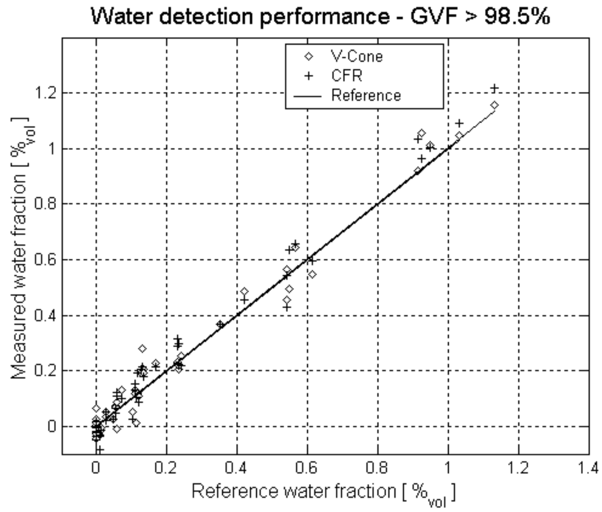

Fig. 10 Water detection accuracy, GVF > 98.5%.

4.2 Flow Rate Measurement

Both the V-Cone and the standard venturi were tested as differential pressure flow elements in the K-Lab test. Both devices were run with upward vertical flow. The V-Cone was tested using the standard pipe wall – cone differential pressure tapping as well as a pipe wall – pipe wall version (see Fig. 11). The two solutions showed a similar performance. The pipe wall to pipe wall version has been chosen in the commercial sensor to avoid deposit of contaminations in the cone in the case of vertical upward flow.

A substantially constant venturi discharge, according to ISO-5197 standard, was observed in the gas test series. In the same test series, the V-Cone sensor showed a velocity dependency that has been modelled using the Dahlstrøm formula [10]:

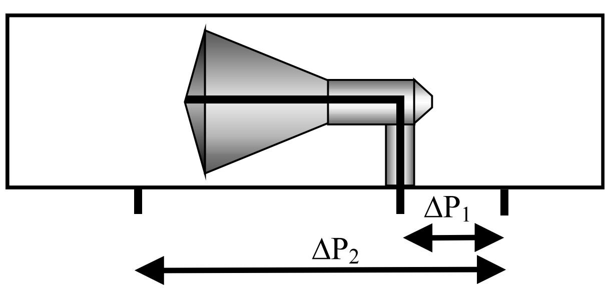

Fig. 11 V-Cone with pipe wall – cone tapping ($\Delta P1$) and pipe wall – pipe wall tapping ($\Delta P2$)

$$C_D = C_{D1} - C_{D2}\left(\frac{10^6}{\mathrm{Re}_g}\right) \tag{6}$$

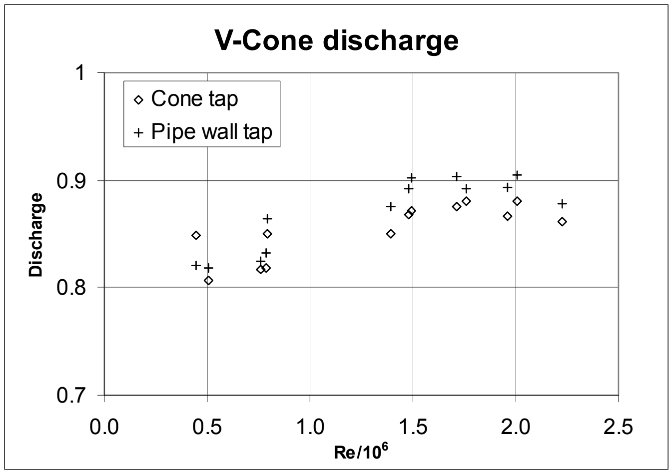

Fig. 12 Measured V-Cone discharge in gas test series

Based on the results of the 2-phase (gas/water and gas/condensate) and 3-phase (gas/condensate/water) test series, it was decided to use a standard de Leeuw model in the venturi based WGM. The V-Cone, on the other hand had a behaviour that was closer to a Chisholm correlation. A minor velocity dependence was, however, also observed in the V-Cone sensor. The V-Cone correlation models will be tested and further developed through a full-scale test of the Mikkel meters at K-lab, scheduled for February 2003.

Some 2-phase gas/water test results are shown in Fig. 13. The isolated flow measurement accuracy in all the 2-phase and 3-phase tests carried out at K-Lab was of size ±2-3%$_{rel}$ for the V-Cone, about 2-2.5%$_{rel}$ for the venturi at GVF > 99% and 3-4%$_{rel}$ for the venturi at GVF=91-99%.

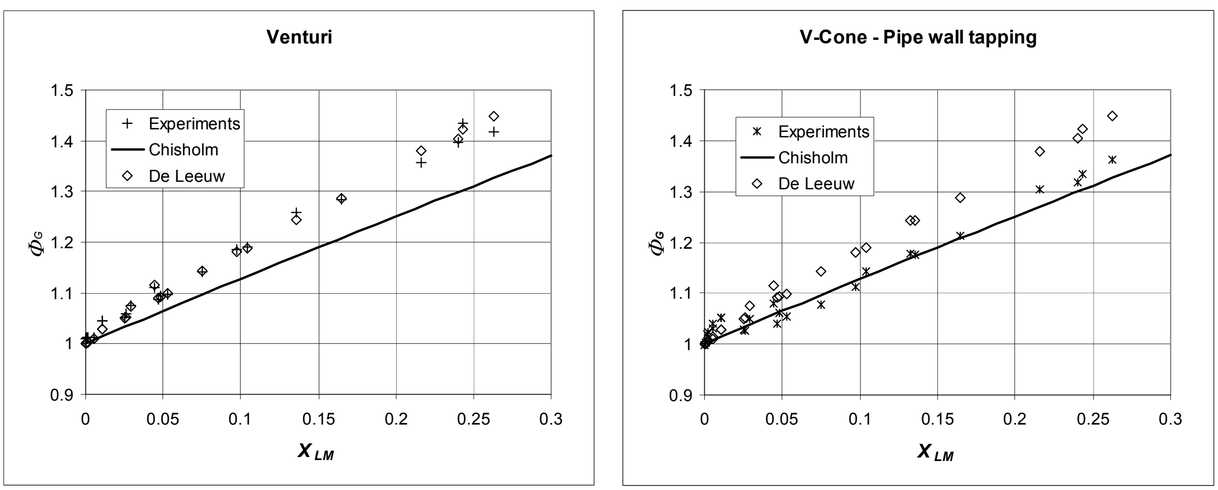

Fig. 13 Observed 2-phase (gas/water) gas multiplier

5 METER SPECIFICATIONS

Based on the K-Lab test results, a prospective specification can be formulated for the V-Cone and for the venturi based WGM solutions. The error propagation due to fraction measurement inaccuracies has been taken into account in the flow rate specifications below. The commercial V-Cone based wet gas meter (Fig. 1 and Fig. 5) is delivered with pipe wall tapping which is equivalent to an up-scaled version of the 2” type tested at K-Lab. The venturi-based solution

(Fig. 6) is assembled of a CFR sensor and a standard venturi that was tested at K-Lab and a type of annular flow converter that has been tested in Porsgrunn in a separate project in 2000.

Measurement output

- Hydrocarbon mass flow rate
- Water mass flow rate
- Water volume fraction at line conditions

Optional output:

- *Gas vol. flow at line or std cond. (PVT calculations)*
- *Condensate vol. flow. at line or std cond (PVT calculations)*
- *Water vol. flow at line or std. cond.*
- *Fluid density from gamma densitometer.*

GVF range: 90-100%
WLR range: 0-100% for GVF > 99%
0-50% for 90% < GVF < 99%

Hydrocarbon flow rate accuracy:

$\pm 3-4\ \%_{rel}$ for GVF > 99% , WLR =0-100%

$\pm 3-5\ \%_{rel}$ for GVF < 99% , WLR =0-50%

$-8-+5\ \%_{rel}$ for GVF < 99% , WLR =50-100% (based on gamma)

Water detection accuracy:

$\pm 0.1\ \%_{vol}$ for GVF > 99% , WLR =0-100%

$\pm 0.2\ \%_{vol}$ for GVF < 99% , WLR =0-50%

Water detection sensitivity:

$\pm 0.01\ \%_{vol}$

6 CONCLUSIONS

Future field developments will include wet gas or gas/condensate fields with a very high GVF. For some of these fields, in particular the subsea fields, the use of wet gas meters that have a water detection capability will be essential.

A new wet gas meter has been developed, which is based on a microwave water detection technology and a differential pressure flow measurement. Performance tests have shown that the meter will be able to detect changes in the water production with a sensitivity better than $\pm 0.01\%_{vol}$, while the absolute accuracy was $\pm 0.1\%_{vol}$ in high GVF (> 98.5%) cases.

The studies have also shown that the microwave-based technology has a much higher sensitivity to variations in the water content than conventional gamma densitometer technology. As an estimator of liquid content, in the case of gas/condensate fields with moderately high GVFs, a gamma densitometer might however be useful.

The hydrocarbon flow rates were measured with an accuracy of size ± 3-5 $\%_{rel}$. At lower GVFs (91-98.5%), the water detection accuracy was $\pm 0.2\%_{vol}$ in cases with WLR < 50% while the water was systematically overestimated and finally failed in the case of water-continuous liquid (WLR>50%).

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8 NOTATION

GVF	Gas Volume Fraction	Q_w	Water flow rate
GOR	Gas Oil Ratio	P	Pressure
WLR	Water Liquid Ratio	T	Temperature
WVF	Water Volume Fraction	ΔP	Differential pressure
α_c	Condensate volume fraction	f_r	Microwave resonance frequency
α_g	Gas volume fraction	f_{vac}	Microwave vacuum frequency
α_w	Water volume fraction	ε_{mix}	Fluid mixture permittivity
α_i	Inclusion fluid volume fraction	ε_i	Inclusion fluid permittivity
σ	Water conductivity	ε_h	Host fluid permittivity
ρ_c	Condensate density	D	Inner diameter
ρ_g	Gas density	C_D	Flow meter discharge
ρ_l	Liquid density	y	Fluid expansibility
μ	Gas viscosity	Φ_G	Two-phase gas multiplier
k	Gas isentropic exponent	β	Flow meter beta (diameter) ratio
Q_c	Condensate flow rate	X_{LM}	Lockhard-Martinelli parameter
Q_g	Gas flow rate	Re_g	Gas Reynolds number