

Magnetic Resonance Multiphase Flow Meter: Gas Flow Measurement Principle and Wide Range Testing Results

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1 INTRODUCTION

This paper describes the principle of quantifying the gas fraction during multiphase flow using the Magnetic Resonance (MR) based multiphase flow meter and provides experimental results obtained during the testing phase of the meter.

The industrialized version of the magnetic resonance based multiphase flow meter has been introduced in 2013 [1]. At that time, the technical concepts for determining the water liquid ratio as well as liquid flow rates were explained. In addition, details of the mechanical construction and first test results were provided.

This paper starts with a brief summary of the liquid measuring principle and continues with a description of the Magnetic Resonance Imaging (MRI) methodology which is used to quantify gas phase fraction and velocity. This explanation is supported with illustrative measurement data. As such, this paper can be understood as an extension of the paper on the Magnetic Resonance (MR) based multiphase flowmeter presented last year[1]. Meanwhile, extensive tests have been carried out with the industrialized version of the MR meter in various test laboratories, covering a wide range of flow rates, GVF's, WLR's, salinities, viscosities and pressures. The results of these tests will be presented in this paper, illustrating the performance of the latest version of the MR-based multiphase flow meter.

2 LIQUID FRACTION AND VELOCITY MEASUREMENT

The MR based multiphase flowmeter discussed in this paper is measuring both fraction and flow velocity of oil, water and gas separately. This is done by exploiting specific properties of hydrogen atoms.

An atom consists of electron(s) and a nucleus. A hydrogen atom consists of only one electron and a nucleus consisting of one single proton (in 99.985% of all cases). This hydrogen proton behaves as a tiny magnet in certain aspects. When hydrogen protons are exposed to a static magnetic field, their random geometrical orientation is changed towards an alignment with the direction of the external magnetic field. The magnetic moment of the protons and the magnetic moment of the external field superimpose such that each proton carries out a precession movement around the direction of the external magnetic field. This is similar to the behavior of a toy top in the Earth's gravitational field. The frequency of that precession movement is proportional to the strength of the external field and can be utilized to create resonance effects.

As a consequence of aligning the orientation of hydrogen protons, a net magnetization is built up by the protons. The development of a net magnetization is a function of time (see Figure 1) and depends on the specific molecular interactions that the hydrogen protons encounter in oil, water and gas. The characteristic time scale for magnetization build-up is referred to as longitudinal, or T_1 , relaxation time. Due to stronger inter- and intra-molecular interactions, hydrogen atoms associated with oil typically magnetize much faster than those bound to water (T_1 , oil < T_1 , water). As illustrated in Figure 1, this difference can be exploited to determine the water-liquid ratio of the mixture flowing in the pipe. At a given flow velocity, the exposure time of hydrogen protons to the external magnetic field depends on the length of the magnets producing the external magnetic field. By using two or more pre-magnetization lengths, a contrast can be created between the NMR signals originating from oil and water because the hydrogen associated with oil requires less time (and hence, shorter magnet lengths) for building up the maximum signal than the hydrogen in water. Since the magnetization behavior in the meter of both oil and water is known, the water liquid ratio can now be determined in both completely and partially liquid filled pipes by comparing signal intensities acquired with different pre-magnetization lengths. Referring to Figure 1, note that the ratio of the signals acquired at different pre-magnetization lengths, as indicated by the grey dots in Figure 1, is directly related to the water liquid ratio, while the signal strength acquired at maximum pre-magnetization length is directly related to the liquid hold-up.

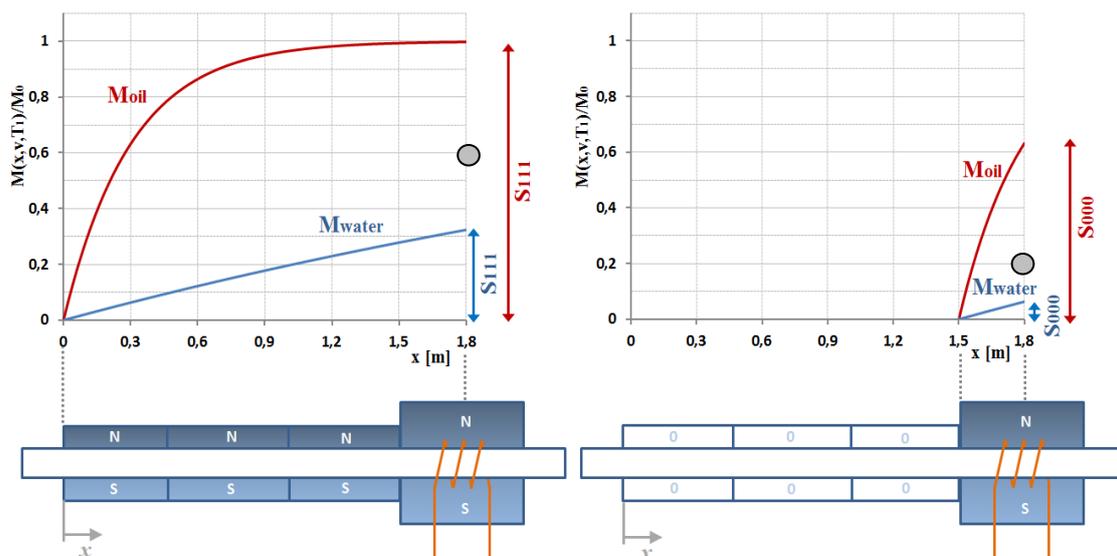


Figure 1 - Build-up of magnetization and, hence, signal levels, for oil and water achieved with maximum pre-magnetization length (left-hand figure) and minimum pre-magnetization length (right-hand figure). The magnetization build-up as shown above holds for a flow velocity, v , of 2 m/s and longitudinal relaxation times, T_1 , of 0.15 s and 2 s for oil and water, respectively. In practice a mixture of oil and water is present leading e.g. to the measured signals as indicated by the grey dots.

The flow velocity is measured by analyzing the signal attenuation as function of time. This technique is referred to as 'convective decay' method. The magnetized protons are entering the location inside the meter where the NMR is being detected (by the Radio Frequency (RF) coil indicated by orange in Figure 1). In order to determine the signal level created by the magnetization build-up, the protons are excited with an electromagnetic pulse sequence by means of an RF

coil. The excited protons, in turn, are generating a signal (echo) that is detected by the same RF coil and subsequently modulated, amplified and processed in the electronics section of the meter.

During the initial RF pulse, only the fluid volume (and associated protons) that is present in the RF coil at the particular time stamp of the first RF pulse is excited. Due to flow, this excited volume is leaving the coil. Subsequent RF pulses, rapidly applied with milli-second time separation, can only manipulate the magnetization of the protons associated with the fraction of the fluid volume that still remains in the RF coil at each particular pulse. This fraction of fluid volume is permanently decreasing and consequently, the amplitude of the detected echo is also linearly decreasing. This concept is illustrated in Figure 2. The higher the flow velocity, the faster the excited volume is leaving the coil, and the steeper is the envelope curve of successively acquired NMR signals.

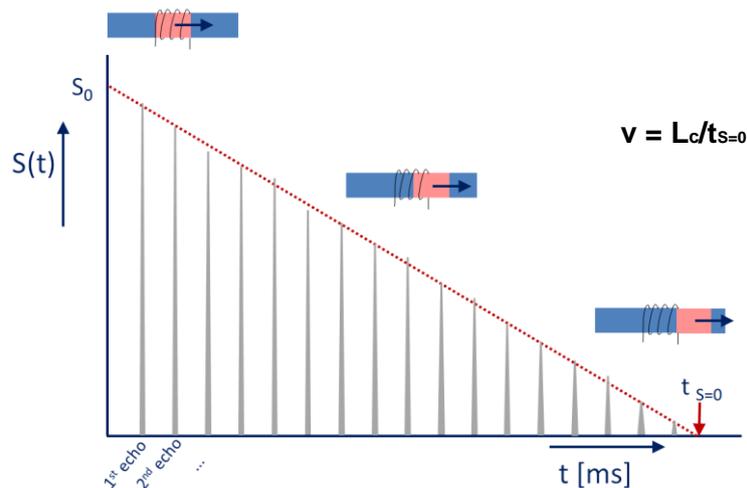


Figure 2 - Velocity determination using the so-called convective decay method. Ignoring magnetic relaxation effects, the measured echo amplitude decreases linearly with time since the excited measured volume is leaving the RF coil due the flow. At a certain time the entire excited measured volume has left the RF coil. The RF coil length divided by the time at which the red dashed line intercepts the horizontal axis yields flow velocity.

The velocity that is obtained from the convective signal decay is a composition of the oil and water velocities. The initial signal amplitude corresponds predominantly to oil if a sufficiently short pre-magnetization length is selected that does not allow the hydrogen atoms associated with water to create a significant magnetization. Consequently, the velocity that is being measured for this pre-magnetization configuration predominantly reflects the oil velocity. This, in combination with the measured water liquid ratio, makes it possible to determine both the oil and water velocities independently.

The reader is referred to [1], [2], [3] and [4] for a more detailed description of the Magnetic Resonance principle and its application in multiphase flow measurement.

3 EXPLANATION GAS MEASUREMENT

3.1 Gas hold-up determination

The MR flow meter is capable of directly measuring the gas hold-up as well as the gas phase velocity. The underlying principles will be explained in this section.

Assume a simplified two phase flow situation comprising a gas-liquid mixture. For this system holds that the sum of the liquid and gas hold-ups equals unity:

$$\lambda_L + \lambda_G = 1 \quad (1)$$

where λ_L and λ_G are the hold-ups for liquid and gas, respectively. Furthermore, we know that the measured signal, $S_{meas.}$, is a superposition of the signals generated by the liquid and gas fractions, respectively:

$$\lambda_L \cdot S_{100\%L} + \lambda_G \cdot S_{100\%G} = S_{meas.} \quad (2)$$

where $S_{100\%L}$ and $S_{100\%G}$ are the signal amplitudes corresponding to 100% liquid and gas filling, respectively. These particular-signals amplitudes are determined as part of the calibration procedure for each meter.

Equation (1) in combination with (2) can be written as:

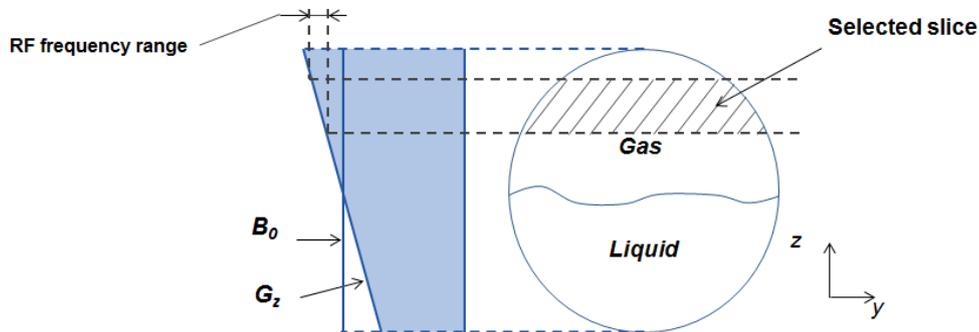
$$\lambda_G = \frac{S_{100\%L} - S_{meas.}}{S_{100\%L} - S_{100\%G}} \quad (3)$$

$S_{meas.}$, $S_{100\%L}$ and $S_{100\%G}$ are known. Consequently, λ_G can be calculated. Considering the strong contrast between the liquid and gas signal amplitudes due to their contrast in hydrogen density, this methodology is a very robust and reliable way to accurately determine the gas hold-up.

This approach can be extended for the situation in which the liquid phase is a composition of oil and water.

3.1 Gas velocity determination

The gas velocity is determined by exploiting the imaging capability incorporated in the magnetic resonance multiphase flowmeter. Similar to Magnetic Resonance Imagers developed for medical applications, the MR multiphase flow meter is capable of producing an image of the spatial distribution of hydrogen protons inside the pipe. This detection principle is further explained in the following paragraphs.



$$f(z) = 2\pi\gamma(B_0 + z \cdot G_z)$$

Figure 3 - Application of a linear magnetic field gradient in the vertical direction, z , makes the proton resonance frequency to become a function of height inside the pipe. By means of an RF frequency band selection, only protons in the

selected slice can be measured. It should be noted that the flow is in the x-direction.

The resonance frequency of detecting a MR signal is directly proportional to the strength of the applied magnetic field, B_0 .

By adding a linear magnetic field gradient, G_z , in the vertical direction, see figure 3, the magnetic field strength varies linearly inside the pipe and now becomes a function of height, as indicated by the blue shaded area. Consequently, the resonance frequency of the protons, f , becomes a function of the height inside the pipe, z .

By means of an RF frequency band selection, only protons in the corresponding resonance frequency band are read out, effectively leading to a slice-selective measurement. Using this spatial information, the velocity as a function of height can be determined. Increasing the intensity of the applied magnetic field gradient enables that the selected slice is sufficiently narrow to ensure that only a single fluid phase is detected and analysed in terms of flow velocity. An example of this data acquisition is shown in Figure 4.

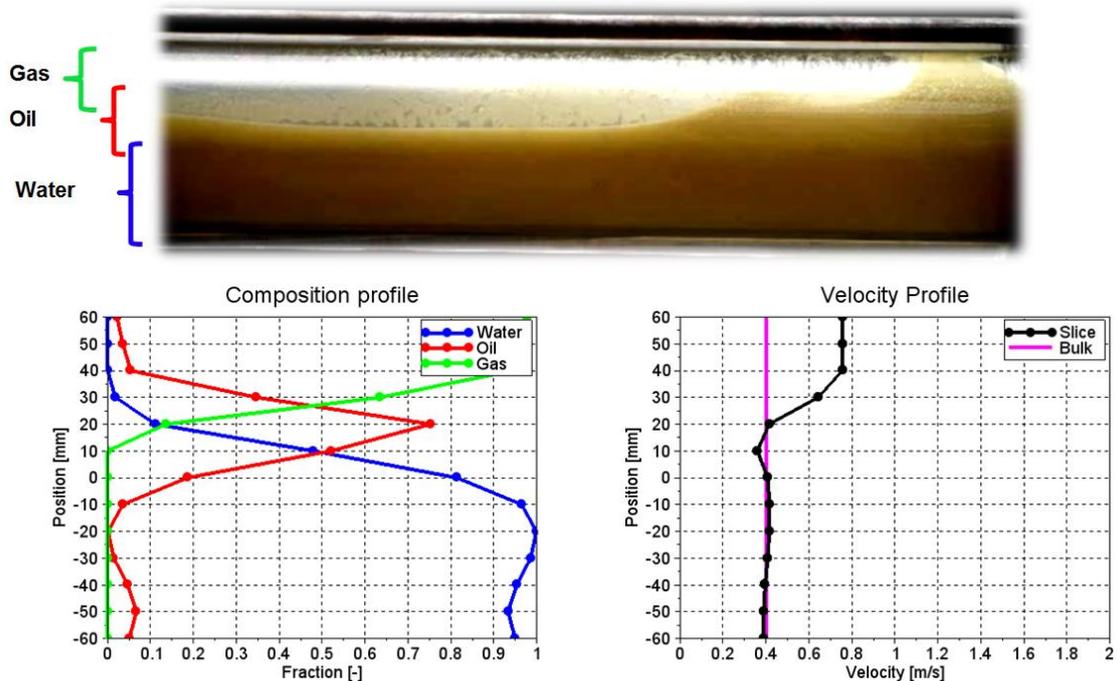


Figure 4 - The lower left-hand figure shows the composition profile for the multiphase stratified wavy flow as shown in the upper figure. In the right-hand lower figure the corresponding time averaged velocity profile is depicted. (Gas: $5.8 (a)m^3/h$, Oil: $1.6 m^3/h$, Water: $6.4m^3/h$, WLR: 80%, GVF: 43%).

4 BRIEF DESCRIPTION OF THE VARIOUS MULTIPHASE TEST FACILITIES BEING USED

The magnetic resonance flow meter has been tested at four different flow loops (see Figure 5). With the exception of the single phase (water) testing at the XCaliber loop in Dordrecht, NL, all flow loops have been visited a number of times with the various generations of the MR flow meter:

- Multiphase flow loop of Southwest Research Institute (SwRI), San Antonio, TX, USA.

- Single phase (water) flow loop (XCaliber loop), Dordrecht, NL.
- Multiphase flow loop of Shell (Donau loop), Rijswijk, NL.
- Multiphase flow loop of DNV-GL, Groningen, NL.

The test conditions of each flow loop are briefly discussed.

SwRI Test facility, San Antonio, Last test in March 2013.

Fresh water, oil (Regal R&O 32 VSI, viscosity about 43 cSt @ 32°C) and methane have been used as test fluids. The operating static pressure and temperature were 82.7 bar(g) and 32°C respectively. The Gas Volume Fraction (GVF) versus Water Liquid Ratio (WLR), as well as gas and liquid flow rates are included in Figures 6 and 7. The flow regimes tested included single phase, stratified, stratified wavy, plug and slug flow. The test results obtained at this loop have been presented before [1], [3], [4].



Figure 5 - Picture of the various flow test loops. Upper left-hand figure: SwRI, San Antonio, USA. Lower left-hand figure: XCaliber, Dordrecht, NL. Upper right-hand figure: Donau, Shell Rijswijk, NL. Lower right-hand figure: DNV-GL, Groningen, NL.

XCaliber Flow loop, Dordrecht, February 2014.

XCaliber is a single phase, fresh water test loop located in Dordrecht, NL. The operating pressure and temperature were 3 bar(g) and 35 °C, respectively. The flow rates have been varied between 15 to 200 m³/h.

Shell Donau multiphase test loop, Rijswijk, NL, February&April 2014

The Donau flow loop is using compressed air for the gas phase. The MR flow meter has been tested using oils of three different viscosities (Renolin 10 cSt, 50 cSt and 120 cSt). Saline water (100 g/l NaCl) is used for the water phase. The line pressure for the experiments with the MR multiphase flowmeter was kept at 3 bar(g), and the line temperature at 40 °C. The Gas Volume Fraction (GVF) versus

Water Liquid Ratio (WLR), and gas versus liquid flow rates that have been tested are included in Figures 6 and 7.

DNV-GL Test loop, Groningen, NL. Last tested in June 2014

The DNV-GL flow loop[5] comprises a multiphase pump, combined with a separator and storage vessels for the different liquid types. A heat exchanger is used to control the temperature of the loop. The complete loop is at test pressure. The reference flow rates for oil and water were measured with Coriolis meters in different ranges. The gas reference flow is measured using ultrasonic flow meters. A Hysys flow model is linked to the data acquisition system to account for phase transition between the reference meters and the MUT due to temperature and pressure differences. The fluids used in this flow loop are Groningen natural gas (81 vol.% CH₄, 14 vol.% N₂), Exxsol D120 API 40 (about 4.1 cSt) and saline water (41 gr/l NaCl).

5 OVERVIEW OF THE MULTIPHASE FLOW METER TESTED RANGE

The MR multiphase flowmeter has been tested over a wide range of conditions at four well known multiphase test facilities. Figure 6 summarizes the GVF versus WLR test points. This diagram shows that the entire GVF and WLR range has been covered systematically. The increased concentration of test points at higher WLR is related to our particular interest of utilizing the MR flowmeter for these conditions.

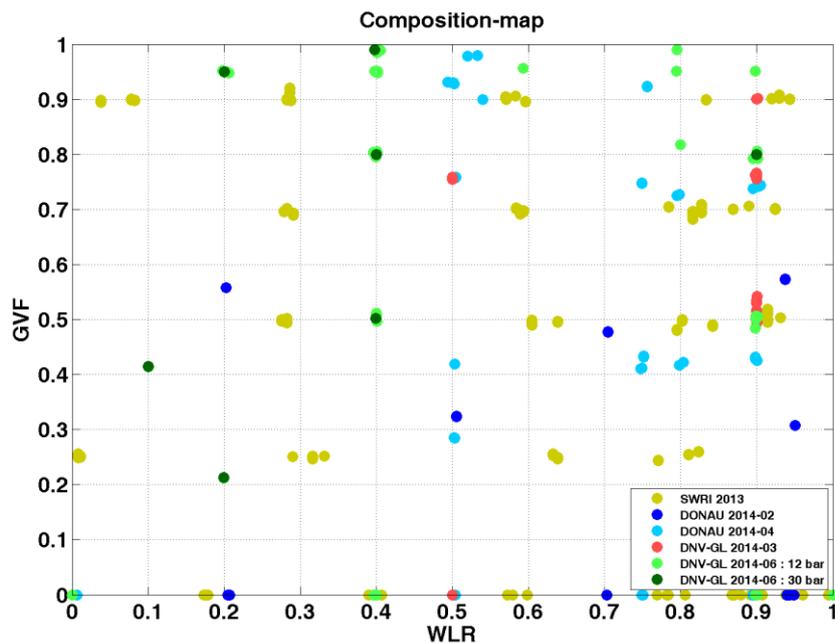


Figure 6 - Overview of all Gas Volume Fraction (GVF) versus Water Liquid Ratio (WLR) test points for the tests at various multiphase flow loops.

Figure 7 shows all test points in the flow map; liquid flow rates versus actual gas volume flow rates. The flow rates for both gas and liquid have been varied across a wide range, covering about two decades of each parameter.

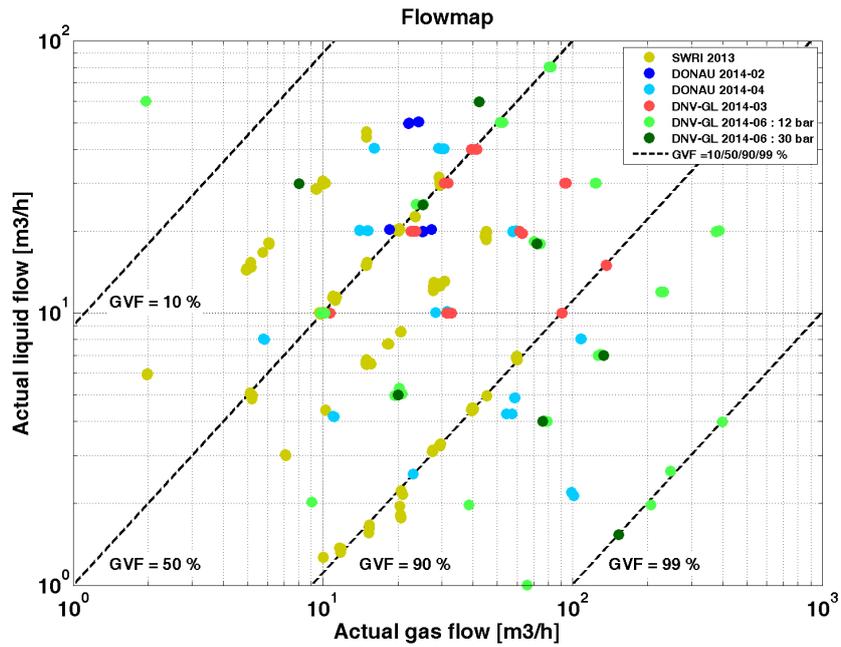


Figure 7 - Overview of the liquid flow rate versus gas flow rate test points for all the tests. Actual flow rates have been used as reference.

Tests at four different pressures have been carried out in the range of 3 to 83 bar(g). The temperature at the various test loops varied from 25°C to 40°C. The salinity varied from 0 g/l (fresh water) up to 100 g/l NaCl concentration. The viscosity of the oil in the multiphase test facilities varied from 4.1cSt (1 cSt on single phase water) up to 43 cSt. An overview of this range is shown in figure 8.

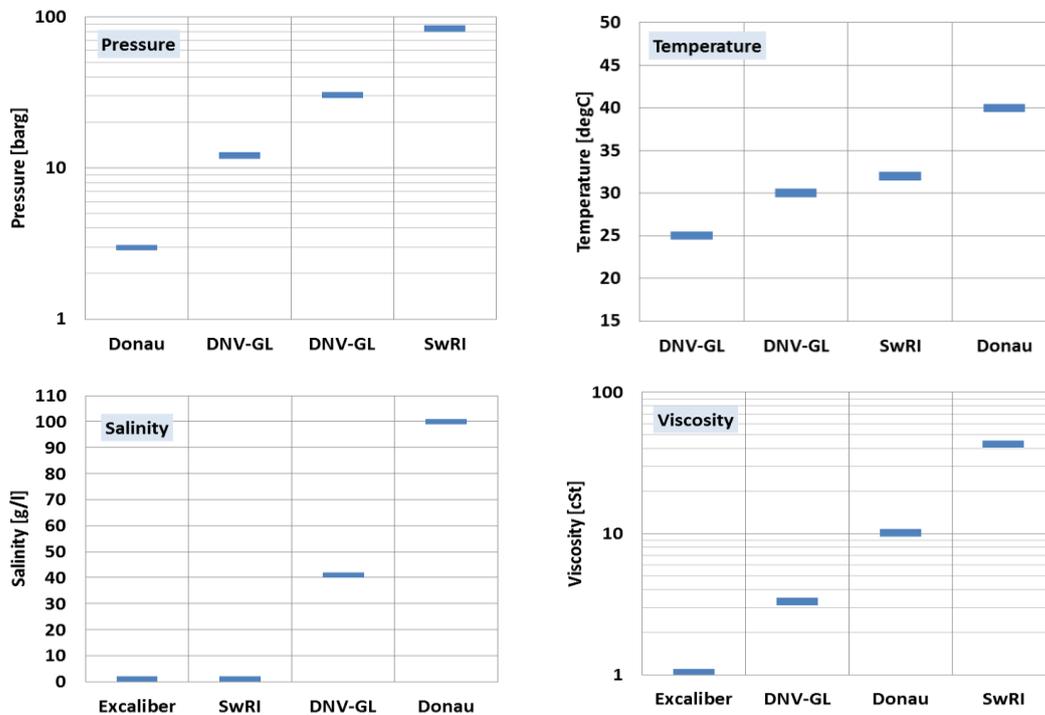


Figure 8 - Overview of the test pressure, temperature, salinity and viscosity.

6 OVERVIEW OF THE TEST RESULTS

Prior to the measurements at DNV-GL, tests at the Donau flow loop of Shell have been carried out. During these tests at the Donau, the calibration parameters of the MR flowmeter were determined that will be used by the data evaluation algorithm. These parameters have been kept constant for the processing and interpretation of data acquired during the tests at the other flow facilities.

Figure 9 shows the test results that have been obtained at the DNV-GL loop in the flow rate map. In the left-hand figure the results are shown for the tests acquired at 12 bar(g) line pressure. The right-hand figures shows the 30 bar(g) test data. The green squares indicate the reference flow rates. The red circles correspond to the measured values (in accordance with [6]).

A number of points draw attention. At first glance, the 30 bar data looks significantly better than the 12 bar data. For the gas measurements this is indeed true. However, closer analysis shows that this is not true for the liquid data.

For the gas phase, it is clear that a lower pressure leads to a lower gas density. This results in a weaker signal generated by the gas, and thus to a lower signal-to-noise ratio (SNR). Detailed analysis of the test data demonstrates that the errors obtained in the gas measurement results can be attributed to the relatively high level of noise of the measured gas signal. To address this finding, the sensitivity of the latest version of the MR multiphase flowmeter has been improved by a factor of three. The result of this improvement is a signal-to-noise level which is comparable to the signal quality of 30 bar as presented in the right-hand figure. This hardware improvement should lead to improved results for lower gas pressures.

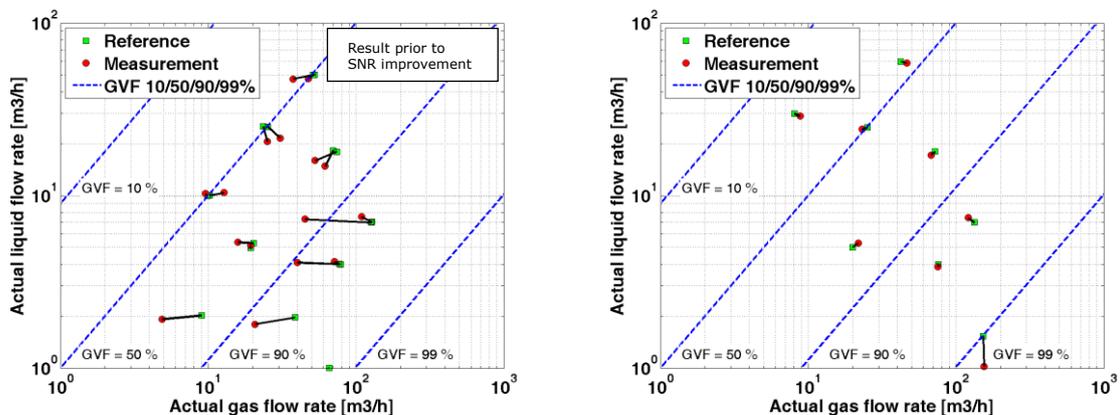


Figure 9 - Flow map with an overview of the test results. The green squares indicate the reference flow rates. The red circles indicate the measured flow rates. The left-hand figure shows the results obtained with 12 bar(g) line pressure. The right-hand figure corresponds to 30 bar(g) line pressure.

The liquid data around the value of 20 m³/h Figure 9 show a larger deviation between measured and reference values. Further analysis of the measured data, and comparison with video recordings of flow behaviour acquired simultaneously through sight glasses during the flow tests revealed that this larger deviation is related to a mismatch between data acquisition frequency and slug frequency. For these particular flow conditions, the video recording illustrated that the slug frequency is noticeably smaller than the typical measurement interval.

A longer measuring time should lead to better averaging of flow rate and fluid fractions, and consequently to better results. This relation is confirmed by the

measurements at 30 bar line pressure with identical actual liquid and gas flow rates. Video recordings demonstrate a more regular slug pattern at 30 bar line pressure, to which the selected data acquisition pattern was better suited.

Figure 10 shows the test results for the 30 bar test conditions in the composition map. The left-hand figure shows the error in the liquid measurements; the right-hand figure the gas results. If the meter's performance would have been inferior for a specific GVF or WLR range, this shortcoming would have become visible in these diagrams. However, both for the liquid and the gas measurements, there seems to be no specific range in which the error deviates significantly.

For all the test points, the error associated with the gas flow measurement is less than 10% of the MV, even though two of the measured points were outside the operating range for this version of the MR flowmeter. For the error associated with the liquid flow measurement, all test points are within 5% of the MV, noticeably both inside and outside the specified operating range. An exception is the liquid measurement at a GVF of 99%. The uncertainty in the quantification of the 1% liquid fraction flowing in the gas stream is 14.5% MV. When related to total volume flow this reading translates to an error of 0.145%, which is still good.

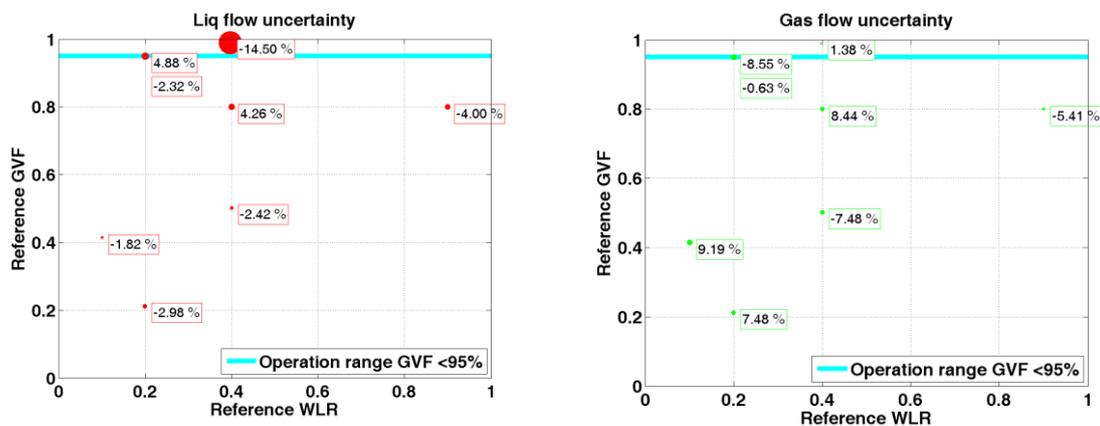


Figure 10 - Overview of the test results in the composition map. The left figure shows the liquid flow measurement error in %MV. The right figure shows the gas flow measurement error in %MV.

The results of the liquid measurements acquired at Shell's Donau flow loop are shown in figure 11. Due to the fact that this installation uses compressed air for the gas phase, no gas NMR signal is generated. Because of the absence of hydrogen in compressed air. As a consequence, the gas velocity cannot be measured. For this reason the 'measured' gas flow was set equal to the reference gas flow during data interpretation.

The measured liquid flow rates correspond well with the reference values. Higher GVF's appear to be associated with larger measurement uncertainties. At the same time, video recordings at these flow conditions show that the flow pattern is very unstable. As discussed in the previous section, this shortcoming will be addressed by selecting longer data acquisition periods, which are expected to lead to an improved precision of the MR flowmeter for these conditions.

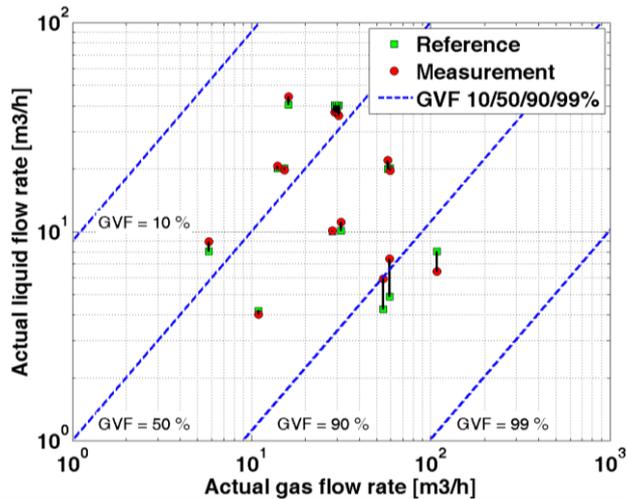


Figure 11 - Overview of the test results obtained at Shell's Donau flow loop plotted on a flow map. The green squares indicate the reference flow rates. The red circles indicate the measured flow rates. Test pressure was 3 Bar(g). As explained in the text above, the 'measured' gas flow rate is set equal to the reference gas flow rate.

Analysis of the data at different water salinities validates that a variation in salinity, and hence, conductivity of the water phase, does not have a noticeable effect on the accuracy of the volume flow measurements. This implies that the accurate WLR measurements obtained with fresh water [1] have also been confirmed for higher water salinities. The insensitivity of the MR flowmeter to emulsification of the oil and water phases has been confirmed as well.

Compared to the results as presented last year, the accuracy of liquid and gas measurements has been significantly improved with the latest generation of the MR flowmeter. This is illustrated by the cumulative error plot as shown in Figure 12.

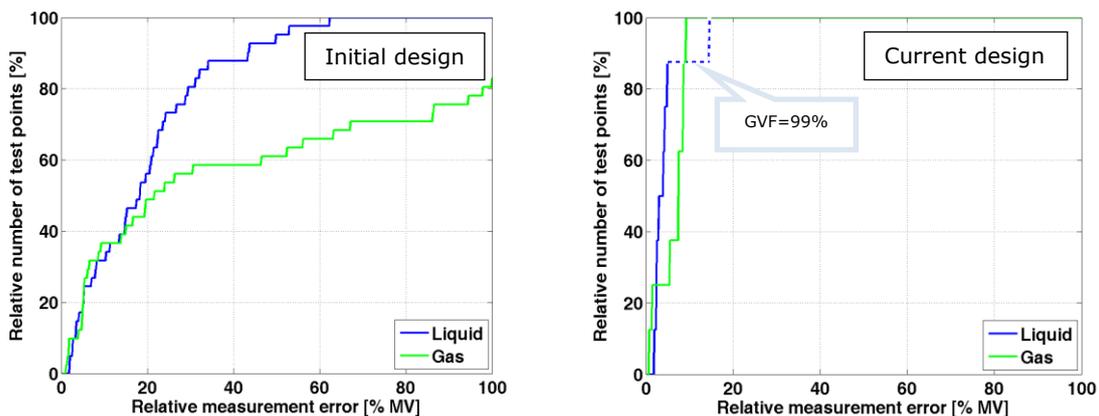


Figure 12 - Cumulative error plot for liquid and gas measurement. Left-hand figure: results obtained at SwRI in 2013 at 83 bar(g). Right-hand figure: result obtained with the improved industrialized MR multiphase flowmeter obtained in June 2014 at 30 bar(g).

For liquid flow, the uncertainty has been reduced by a factor of 3 to 6 compared to earlier results reported. For gas flow, the improvement is significantly higher as increasing the meter's sensitivity for detecting small signals, as well as further improving the automated data evaluation algorithm, resulted in a reduction of

measurement error by approximately a factor of 8. We repeat that the same evaluation algorithm, including constant calibration parameters, has been used for the entire application range (flow, GVF, WLR, salinity, temperature and pressure).

7 SUMMARY AND CONCLUSIONS

This paper provides an explanation of the physical concept for the measurement of gas fraction and gas velocity using magnetic resonance technology. Utilizing the concept of magnetic resonance imaging, it has – for the first time – be possible to directly quantify the flow of a free gas phase during multi-phase flow at industrial conditions.

The improved and industrialized design of the MR multiphase flowmeter has been tested at four different flow loops over a wide range of conditions of gas and liquid flow rates, GVF, WLR, pressure, salinity and viscosity. This paper provides an overview of the results of these tests.

Progress in both hardware development and the data interpretation algorithm has resulted in a significant improvement in measurement accuracy both for liquid flow (factor of 3 to 6 improvement) and for gas flow (factor of 8) characterization compared to the previous prototype version. The high accuracy of the WLR determination has been proven again by additional measurements. The experiments have demonstrated that a variation in water salinity neither affects the accuracy of WLR, nor the accuracy of the liquid and gas volume flow rate.

The tests have shown that the MR flowmeter's accuracy of gas and liquid measurement is not dependent on volume flow rate, below a GVF of 0.95. It was realized that the data acquisition period of the flow meter needs to be carefully adjusted to the slug frequency in order to acquire representative data.

Line pressure starts to affect the accuracy of gas flow measurements once the pressure is below approximately 10 bar. Analysis of acquired data showed that this uncertainty is related to a relatively high noise level. Further hardware improvement has resulted in a reduction of the data noise level by more than a factor of 3. This leads to a proportionally better performance of the gas measurements at lower pressures.

8 ACKNOWLEDGEMENTS

The authors of this paper like to express their appreciation to the entire development team for the tremendous amount of work that has been done throughout the last year. Further acknowledgement is made to the various operators of the flow facilities at which the meter has been tested.

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