MULTIPHASE MEASUREMENT SYSTEM WITH FULLY REDUNDANT MEASUREMENTS TO IMPROVE ACCURACY AND SIMPLIFY MAINTENANCE

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1. Abstract

Multiphase flow meters have been accepted and used by the industry for reservoir management and production allocation for several years. Multiphase metering is a fairly new technology that is an attractive alternative to test separators due to reduced field development and maintenance costs in addition to “real time” information as opposed to long term averages. However, multiphase metering technology is not yet very well understood by all field-operators, which makes it more challenging to verify correct operation and further to detect and isolate failures compared to conventional test separators. Traditionally, three phase “measurements” has been performed by separating the flow and measuring at single-phase conditions. Single-phase measurements are well understood by the industry and although the measurement uncertainties of a test separator in many cases are underestimated due to the operational limitations and maintenance requirements, operators normally have procedures and skilled personnel to ensure reliable measurements.

Multiphase measurement differs from a traditional single-phase measurement system by simultaneously performing multiple measurements to measure multiple flow rates. Since the final results are based on a combination of several measurements, any error in just one of the measurements may affect one, several or all the derived flow rates. This aspect of multiphase metering adds to the complexity of deriving simple procedures for maintenance and proving of a multiphase flow meter. Consequently, operators are reluctant to remove the test separator as a proving mechanism to fully take advantage of the cost benefit by using multiphase flow meter. This paper describes a system that can justify omitting the test separator as a proving mechanism by adding two independent and redundant systems to a standard MFI MultiPhase Meter. The system is an integrated part of the MFI MultiPhase Management System (MMS) and enables operators to extend savings in investment and operating expenditures gained from multiphase metering technology.

2. System Components

The system consist of the following main components:
1) MFI MultiPhase Composition Meter*
2) MFI MultiPhase Cross-Correlation Velocity Meter. *
3) Venturi Velocity Meter.
4) Dual Temperature, Pressure and delta Pressure transmitters.
5) PVT Module.
6) MultiPhase Management System (MMS)

*) Integrated part of a standard MFI MultiPhase Meter.

2.1. Composition Meter

The composition and cross correlation sensor (MFI MultiPhase Meter Sensor) is a compact, straight spool piece with no moving parts and no significant pressure drop. A four-inch sensor, as shown in figure 1 below, is less than 700 mm long.

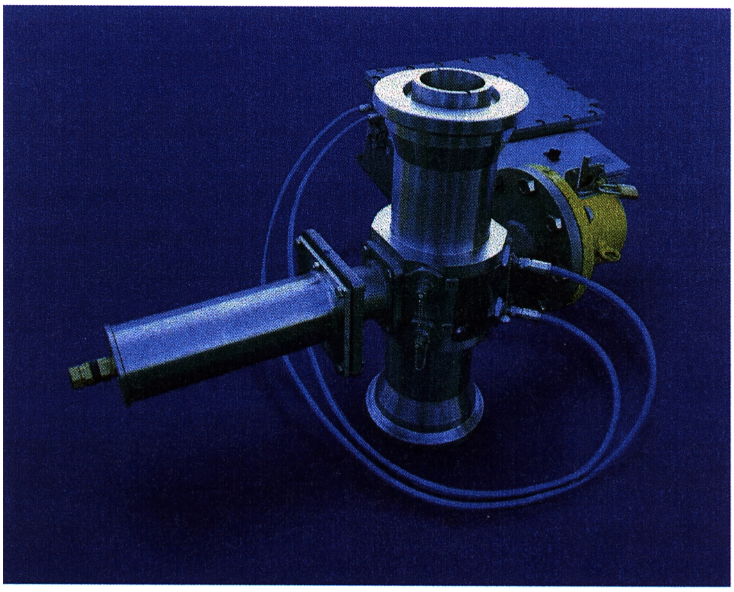


Fig. 1 - 4" MFI MultiPhase Meter. The sensor is a compact, straight spool piece with no moving parts and no pressure drop. A four inch sensor is less than 700 mm long and used to measure the composition and velocity by cross-correlation.

Measurement of the multiphase composition is based on measurement of dielectric constant of the multiphase mixture using a patented microwave technique together with measurement of gamma ray absorption based on a standard single energy gamma ray densitometer. These two measurements together with the sensor area provide three equations sufficient to calculate the oil, water and gas fraction as listed below.

Unknowns: %Oil, %Water and %Gas in the cross section of the pipe.

Equations:

$$(1)\sum(\Phi_{oil}+\Phi_{water}+\Phi_{gas})=100\%$$

$$(2)\Phi_{oil}\times\rho_{oil}+\Phi_{water}\times\rho_{water}+\Phi_{gas}\times\rho_{gas}=\rho_{measured}$$

$$(3)\Phi_{oil}+\Phi_{water}+\Phi_{gas}=f(\Phi_{oil},\Phi_{water},\Phi_{gas},\varepsilon_{oil},\varepsilon_{water},\varepsilon_{gas},\varepsilon_{measured})$$

Where:

Φ = Volume Fraction

ρ = Density at line conditions.

ε = Dielectric constant at line conditions.

As shown in equation three, the composition meter must be calibrated with the dielectric constant of oil, water and gas. The dielectric constant of water is a complex variable of the form:

$$\varepsilon_{water}=\varepsilon'+j\varepsilon''$$

Where:

$$\varepsilon'=f(Temperature)$$

$$\varepsilon''=f(Conductivity)$$

Consequently, in order to calibrate the composition with the dielectric constant for water, only the water conductivity is required as calibration input. Alternatively, the meter itself can be filled with produced water and used to measure the water conductivity.

Most other multiphase meters require that the sensor must be filled with oil and gas in order to calibrate the composition measurement. The MFI Multi-Phase Meter, on the other hand, does not have this requirement due to the well-defined correlation between hydrocarbon density and dielectric constant as shown in figure 2 below.

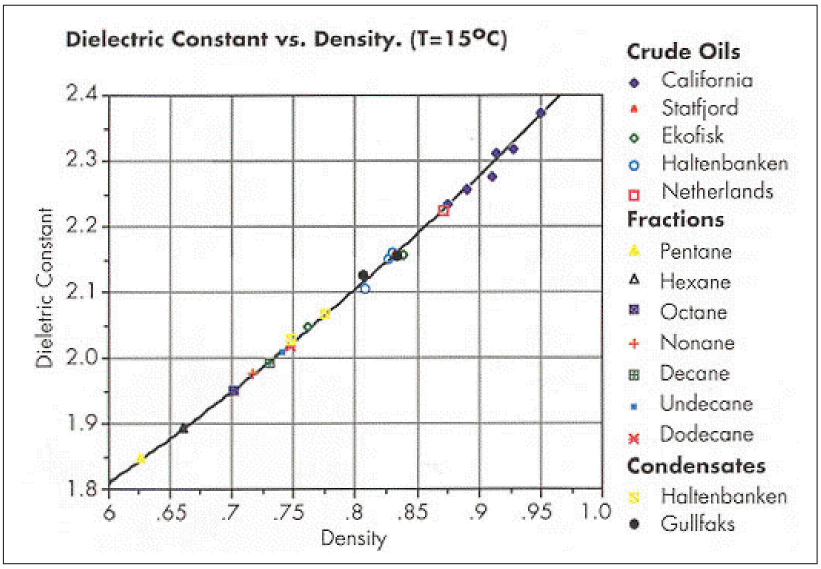


Figure 2: Relationship between hydrocarbon density and dielectric constant at microwave frequencies.

This correlation is only valid for microwave frequencies and can not be used for low frequency measurements such as capacitance and inductance. In addition, Roxar has patented this relationship in connection with hydrocarbon measurements.

2.2. Cross Correlation Velocity Meter

Roxar has in qualification tests at Porsgrunn (7 international oil companies), Gannet (Shell), Humble (Texaco), Trecate (Agip) and Pecorade (ELF) shown that the volumetric MFI Cross Correlation velocity meter and mass based Venturi velocity meter have almost equal performance. The MFI Cross-Correlation velocity meter is in addition the only meter of its kind being able to cross correlate on fine bubble flow and mist/gas flow.

The Cross-Correlation velocity meter uses two identical microwave sensors (such as used in the composition sensor) separated by a known distance in the pipe to measure velocity. By statistically comparing measurements from the upstream sensor with those of the downstream sensor using cross-correlation methods, one can determine the mean transit time for the mixture to move between the sensors. The sensor spacing and the measured transit time give velocity.

The sensitivity of the Cross-Correlation Meter is unparalleled and the MFI Cross-Correlation Meter works for all flow regimes including fine bubble flow. Furthermore, Roxar has broad experience with Cross-Correlation on different process conditions ranging from a few bars and slugging conditions to several hundred bars and stable flow. Our experience is ranging from low-pressure conditions where the variation in the signal is several thousand percent, to very high-pressure conditions, where the variation is less than 0.01%. Figure 3 to figure 6 show two examples of cross-correlation data at two different flow regimes plotted at the same scale. Figure 3 is an example of bubble flow conditions. Although the amplitude is small, there is a clear correlation between the signals giving the corresponding cross correlation peak of figure 4.

At slugging flow conditions, as shown in figure 5, the amplitude variation is much greater since the variation in the flow is greater. From cross-correlation data in figure 5 it is possible to see three gas slugs, several large gas bubbles and many small bubbles giving a corresponding cross-correlation peak as in figure 6. The information contained in the signals also provides useful information regarding the slip between liquid and gas. Roxar has developed a slip flow model to determine the gas and liquid velocities respectively from the measured velocity. Among other inputs, this model uses the statistical data from the composition and the velocity meter. These two velocities are combined with the readings from the composition meter to obtain the actual oil, water and gas flow rates. The Cross-Correlation Meter has a number of advantages compared to other multiphase velocity meters (including Venturi Tubes):

- Turn-down ratio of up to 35:1
- No moving parts
- None intrusive
- High sensitivity
- It also functions with zero water cut and fine bubble flow such as might be present during early production, liquid slugs in long pipelines or high pressure applications
- No differential pressure taps and tubing that can foul, partially fill or leak, or dP transmitters that can drift
- Easily used in high pressure systems without sacrificing accuracy

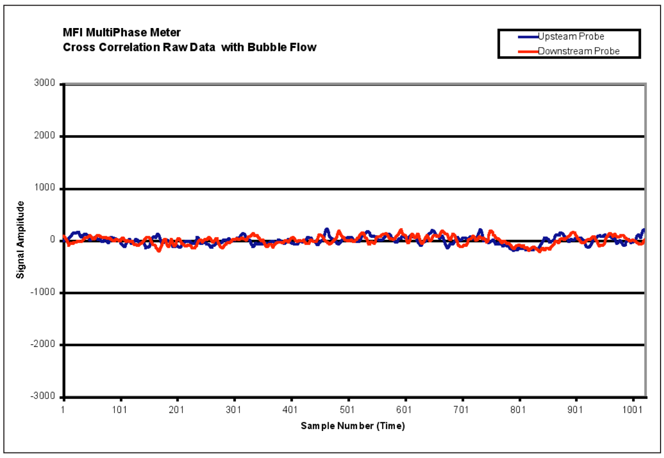


Figure 3:
This is an example of bubble flow conditions. Although the amplitude is small, there is a clear correlation between the signals.

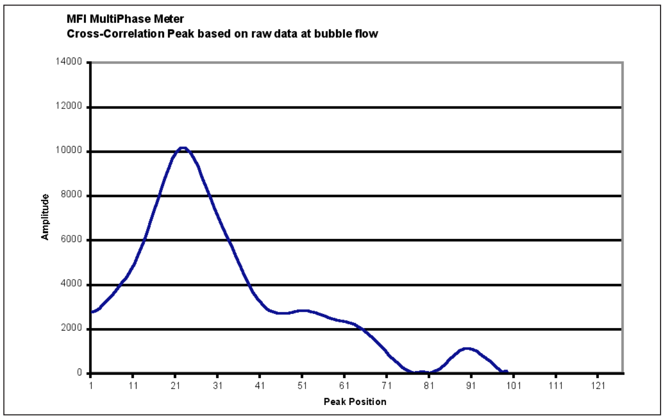


Figure 4:
Corresponding cross correlation peak for bubble flow.

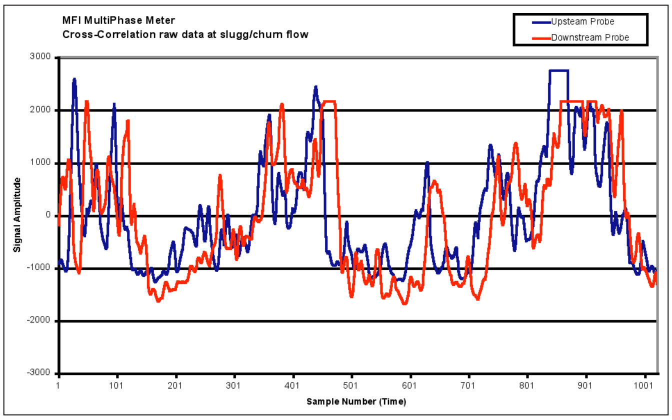


Figure 5:
Cross correlation data at slug/churn flow. The amplitude variation is much greater compared to figure 3 since the variation in the flow is larger. From cross-correlation data it is possible to see three gas slugs, several large gas bubbles and many small bubbles.

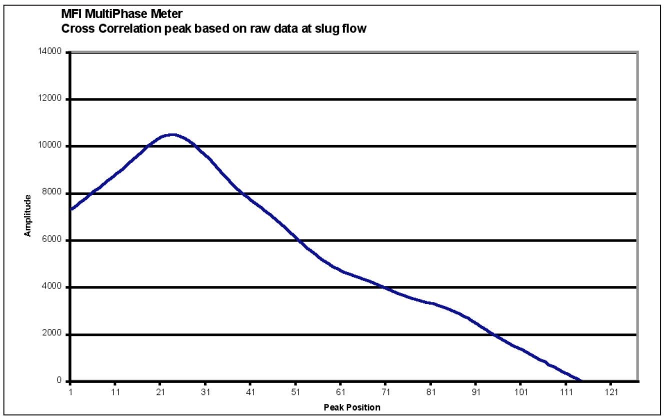


Figure 6:
Corresponding cross correlation peak for slug/churn flow.

2.3. Venturi Velocity Meter

The venturi velocity meter is essentially measuring the mass flow of the multiphase mixture. Combining the total mass flow measurement from the venturi meter with the composition measurement provides a measurement of the volumetric flow rates comparable towards the Cross Correlation velocity meter.

2.4. PVT Module

The PVT module calculates the oil and gas densities in addition to the gas oil ratio (GOR) at any given temperature. Entering the mole fraction, mole weight and density of the hydrocarbon fractions of the well enable configuration of the PVT module. The PVT module can be used to calculate the oil and gas density and GOR at any pressure and temperature. Consequently, the module serves multiple purposes such as calibration values for oil and gas density for the MultiPhase Meter and conversion to other temperature and pressure conditions such as standard or “test-separator” conditions.

In addition, the PVT module provides a redundant “measurement” of the GOR. The multiphase meter is measuring the GOR, which is derived based on a combination of the oil and gas density calibration from the PVT module, measured, GVF and velocities.

The PVT module can also be used to alter the expected hydrocarbon fraction (mole weight, density and fraction of components) based on a known oil and gas density and GOR. This function can be used to “calibrate” the PVT composition towards measurements from a test separator, or as a part of an iteration process between the PVT module and the MFI MultiPhase Meter.

2.5. MultiPhase Management System

The MFI MultiPhase Management System (MMS) is the overall system for managing one or several MFI MultiPhase Meters. The MMS is implemented on standard PC-based software and hardware, and will for the user be seen as a windows based, easy to use graphical Man Machine Interface. From the graphical user interface of the MMS the multiphase meters can be configured, calibrated, diagnosed and operated.

In addition, the large amount of information available from the multiphase meter is stored in a standard SQL database. The use of a standard SQL database for data storage results in significantly easier data utilisation and distribution. Connected to a remote accessible network, the data from the multiphase meter can be on-line processed and analysed from locations far away from the meter itself.

- PVT package for conversion of flow rates to user specified pressure and temperature conditions, and automatic density calibration
- Preventive maintenance routines to verify operation and measurement with redundant transmitters and measurement principles.
- Independent Software package for remote use of the data available from the SQL Database (trending, pre-defined reports, etc)
- Simulation package for re-calculation of the logged raw data.
- Well Management Module for data logistics and analyse.

A block diagram of the MMS modular system is shown in figure 7.

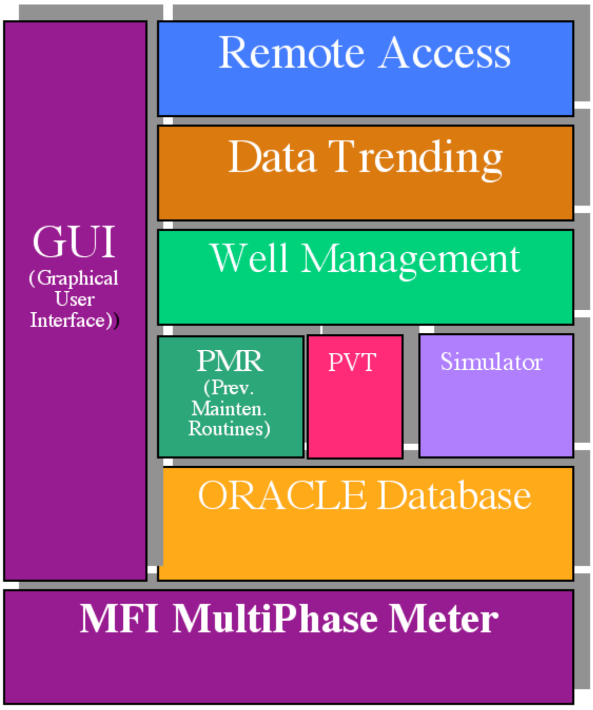


Figure 7: MultiPhase Management System (MMS). A modular program to fully take advantage of the abilities within multiphase measurements.

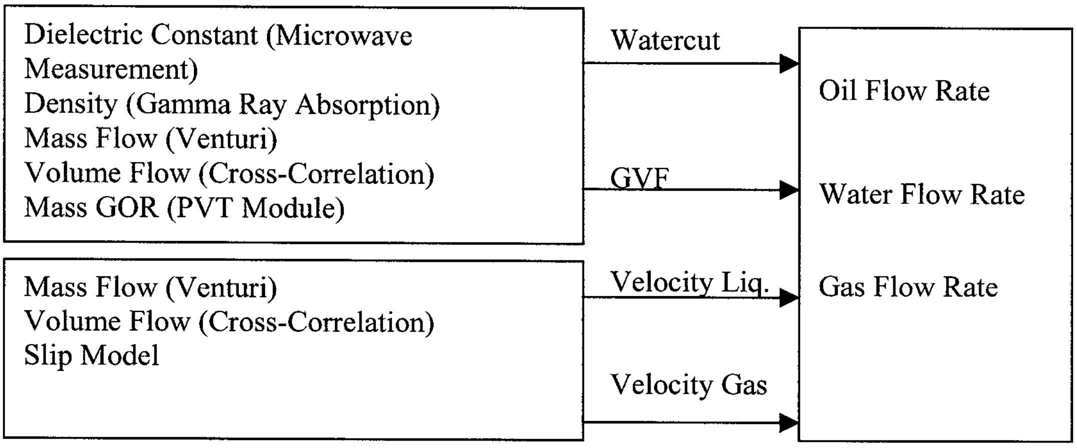
3. System Description

3.1. System Overview

Normally, metering equipment are at regular intervals taken out of service and send to a laboratory for calibration and maintenance. Alternatively, calibration can be carried out on the site using a proving system following a regular calibration schedule. In both cases, calibration and maintenance is both costly and time consuming and in most cases calibration and maintenance are carried out on instruments that are fully within its specification. As a consequence, it is becoming more common to use dual redundant system such that calibration and maintenance only are performed if the two measurements differ by a predefined amount.

A similar methodology called PMR (Preventive Maintenance Routines) has been adopted to the MFI MultiPhase Meter based on redundant measurements from "well known" measurements principles.

The MFI MultiPhase Meter has in several independent qualifications tests shown a very good match between the Cross-Correlation and venturi velocity meter over the entire operating envelope of the meter. The Cross-Correlation velocity meter is a volumetric measurement principle whereas the venturi velocity meter is based on mass flow. Combining the two measurements give redundancy and a means to improve the accuracy of the overall velocity measurement. The composition measurement (GVF and watercut) is based on measurement of dielectric constant (microwave measurement) and density (gamma radiation absorption measurement). Since the venturi velocity measurement is based on mass flow and Cross-Correlation velocity is based on volumetric flow, adding a venturi to the measurement system also provide a means to verify the composition measurement. The PVT module can also be used as an independent source to verify the composition measurement. The PVT module calculates the oil and gas density in addition to mass ratio between oil and gas (mass GOR) based on the mole fractions and densities of the hydrocarbon components of the well fluid. Consequently, the PVT module provides a redundant measurement to the combination of the watercut GVF and slip measurement. A block diagram of the components involved in the calculations is shown below:



To further enhance the independent operation of the Meter, the Preventive Maintenance Routines include redundant temperature and pressure transmitters in addition to the PVT module.

The system is implemented with automatic routines for quality control of the redundant items based on user configured limits, and alarms will be generated when the redundancy is out of synchronization. Upon these alarms, the user can monitor with the system to find the cause of the discrepancy. The system can also provide the user with procedures for how to handle inconsistencies.

3.2 Measurement Uncertainty

The performance specification at 90% confidence level is:

• Liquid Flow Rate Accuracy	± 6% of reading for GVF less than 0,85 ± 10% of reading for GVF greater than 0,85
• Gas Velocity Accuracy	± 10% of reading
• Water Cut Accuracy	± 2% absolute for GVF 0 - 0,6 ± 3% absolute for GVF 0,6 - 0,75 ± 4% absolute for GVF 0,75 - 0,9 ± 5% absolute for GVF above 0,9
• GVF Accuracy	± 1,5% absolute for GVF less than 0,6 ± 2% absolute for GVF greater than 0,6

The MFI multiphase meter measures the oil, water and gas mass flow rates at actual conditions. In order to do so, it needs to be calibrated with the oil, water and gas density together with the water conductivity. Any error in the oil or gas density calibration values will typical affect the measured gas to oil ratio while the measured hydrocarbon mass flow rate remains almost unaffected. The reason for this is the MFI patented “AutoZero” correlation between dielectric constant and density for hydrocarbon as shown in figure 2. This effect is demonstrated in simulations of three cases as shown in figure 8-13 below. For each case a variation of ±10% of the oil and gas density is introduced and the relative change in the oil, gas, water and hydrocarbon mass flow rate is shown in the graphs.

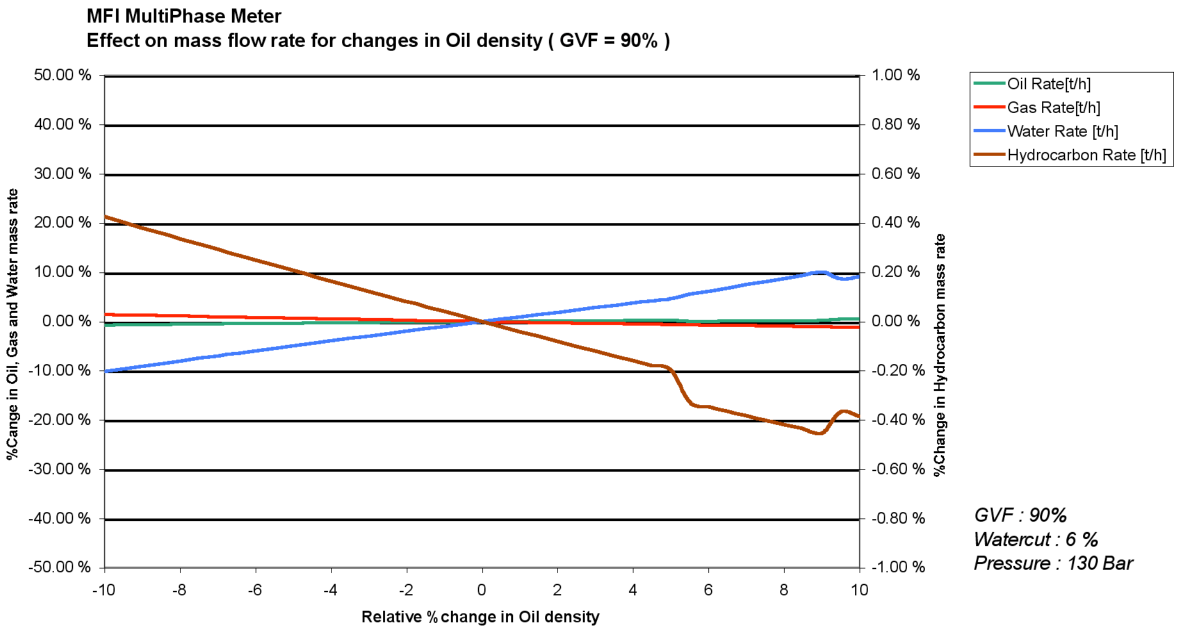


Figure 8: Effect on mass flow rates as a function of calibration value for oil density.

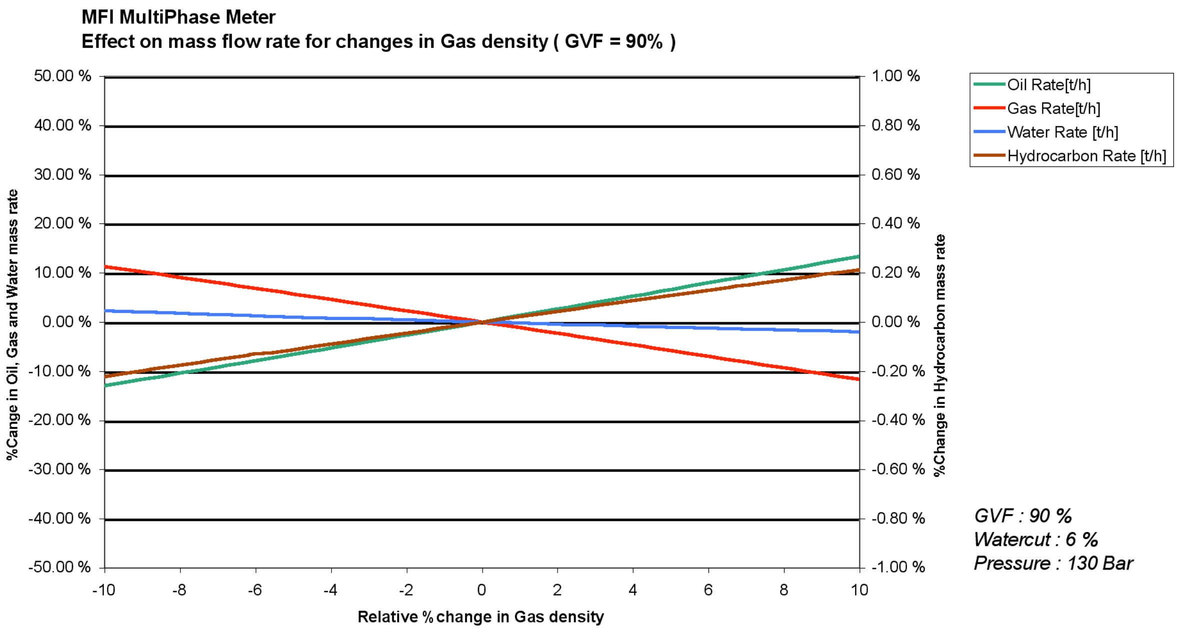


Figure 9: Effect on mass flow rates as a function of calibration value for gas density.

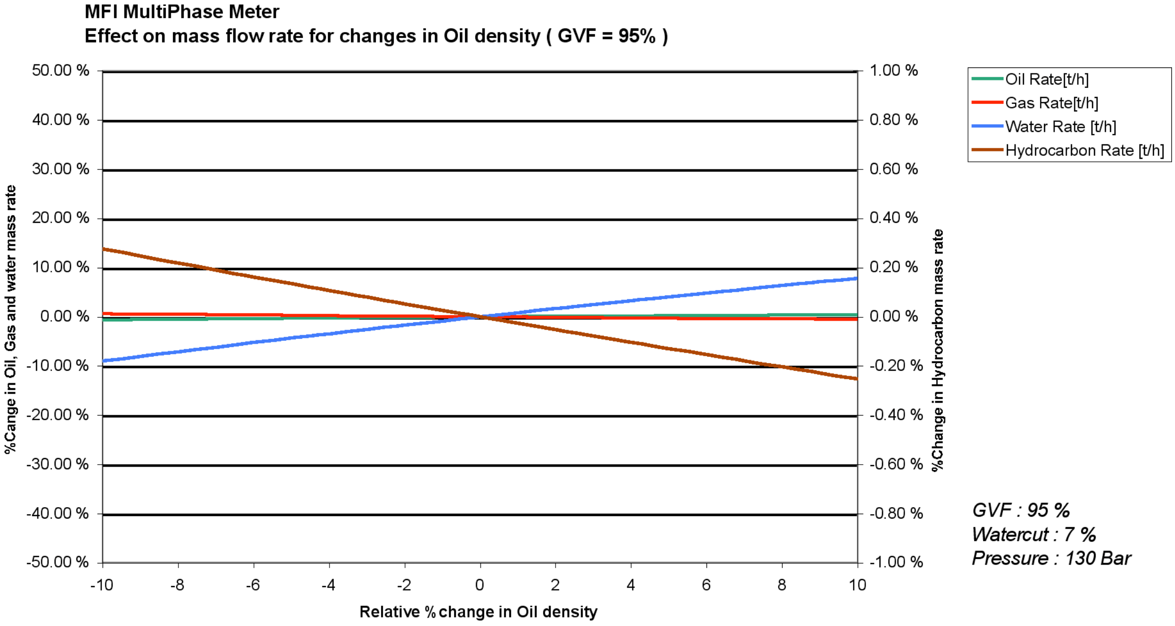


Figure 10: Effect on mass flow rates as a function of calibration value for oil density.

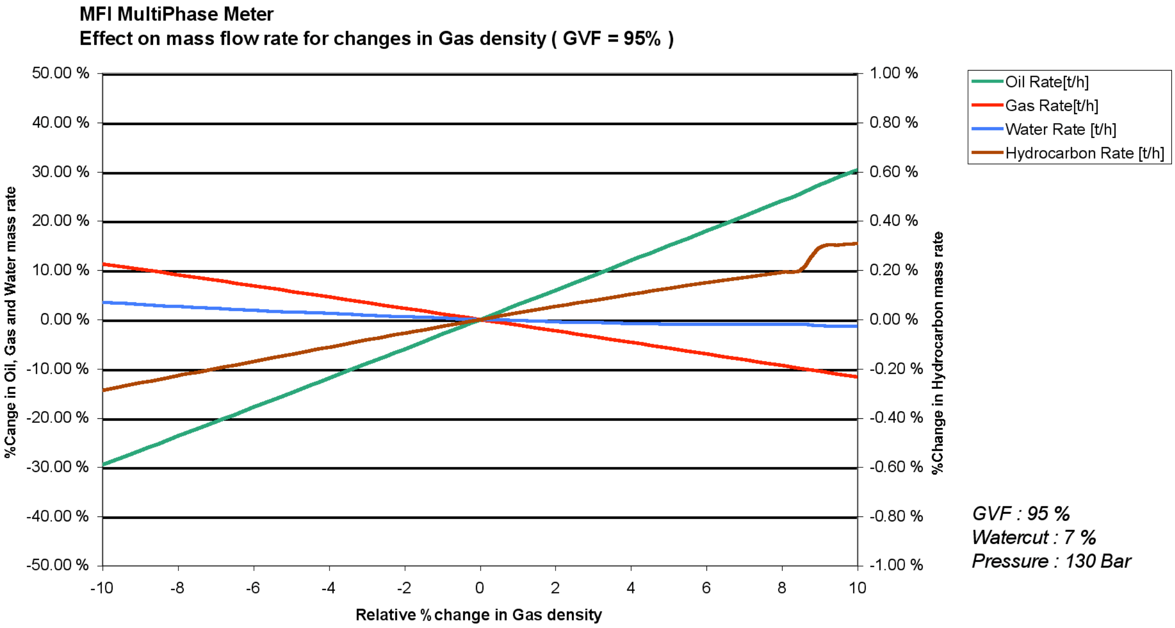


Figure 11: Effect on mass flow rates as a function of calibration value for gas density.

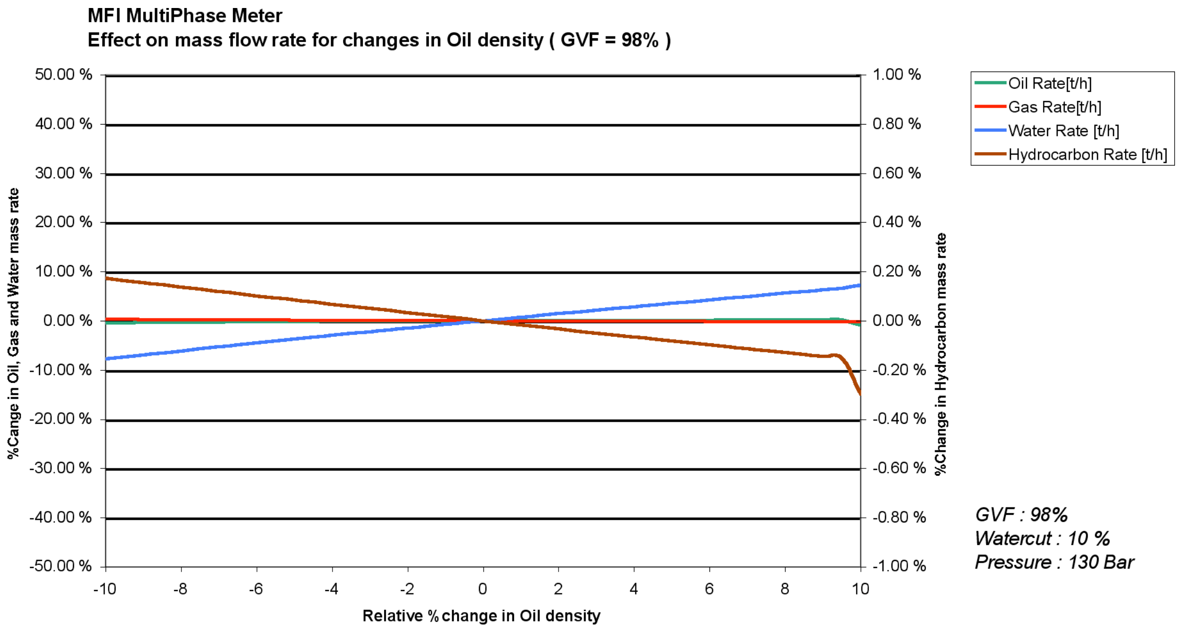


Figure 12: Effect on mass flow rates as a function of calibration value for oil density

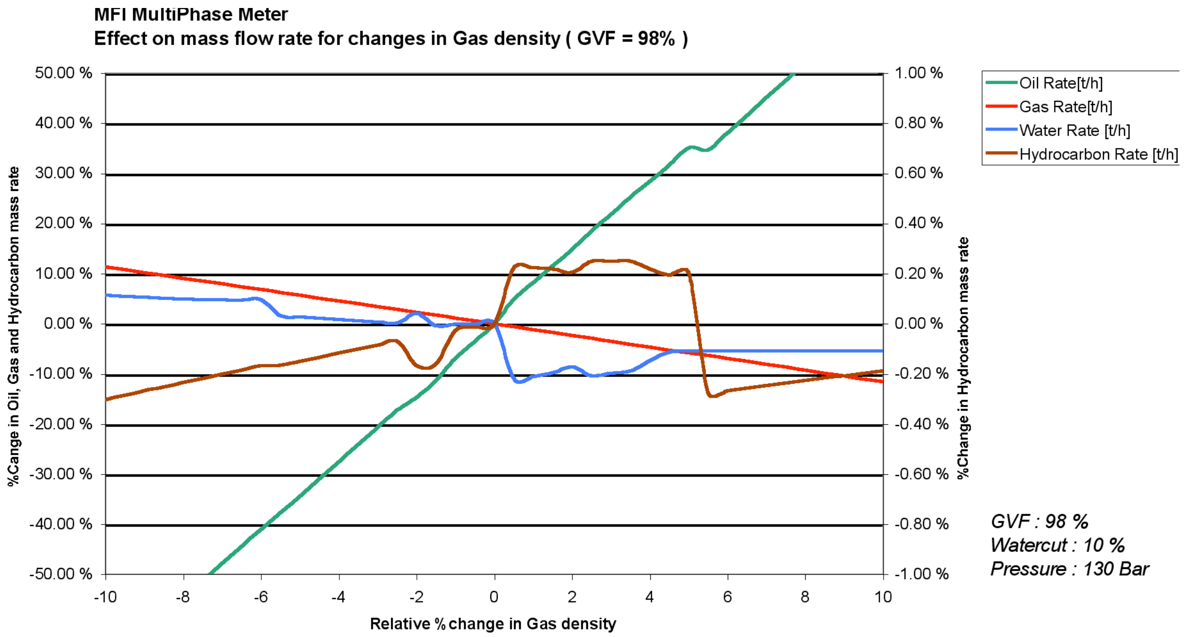


Figure 13: Effect of mass flow rates as a function of calibration value for gas density.

The effect on the measurements for all the above listed cases are summarized in the table below:

Composition		**Relative Change[%]**		**Measurement effect[%]**			
GVF	Watercut	Density Oil	Density Gas	Oil	Water	Gas	**Hydr. Carb.**
90 %	6 %	10 %	0 %	0.6 %	0.6 %	9.0 %	**0.28 %**
90 %	6 %	0 %	10 %	20.5 %	3.5 %	11.5 %	**0.30 %**
95 %	7 %	10 %	0 %	0.7 %	10.0 %	1.5 %	**0.40 %**
95 %	7 %	0 %	10 %	13.5 %	2.2 %	11.5 %	**0.22 %**
98 %	10 %	10 %	0 %	0.9 %	7.2 %	0.3 %	**0.30 %**
98 %	10 %	0 %	10 %	68.0 %	5.7 %	11.6 %	**0.30 %**

As seen from the graphs, the hydrocarbon mass flow rate is far less sensitive to errors in the hydrocarbon density calibration values compared towards the oil and gas flow rate. E.g., whereas the relative error on the oil mass flow rate may be as great as 60-70 % in the event of a 10% change in oil and gas density calibration values, the relative error on the hydrocarbon mass flow rate is within 0.4%. This feature is due to the well-defined and “proprietary” correlation between hydrocarbon density and dielectric constant for dielectric measurements in the microwave frequency region.

4. Case Study

Discrepancies in the measurement system can be detected comparing the redundant measurement variables. Any difference between redundant measurement beyond predefined limits may originate from failures in the measurement system, changes in the well properties such as a compositional change of the hydrocarbon fraction, water salinity changes or internal deposits such as wax or scale in the multiphase sensor. Any discrepancy in the measurement system can be detected and isolated by monitoring the following variables over time:

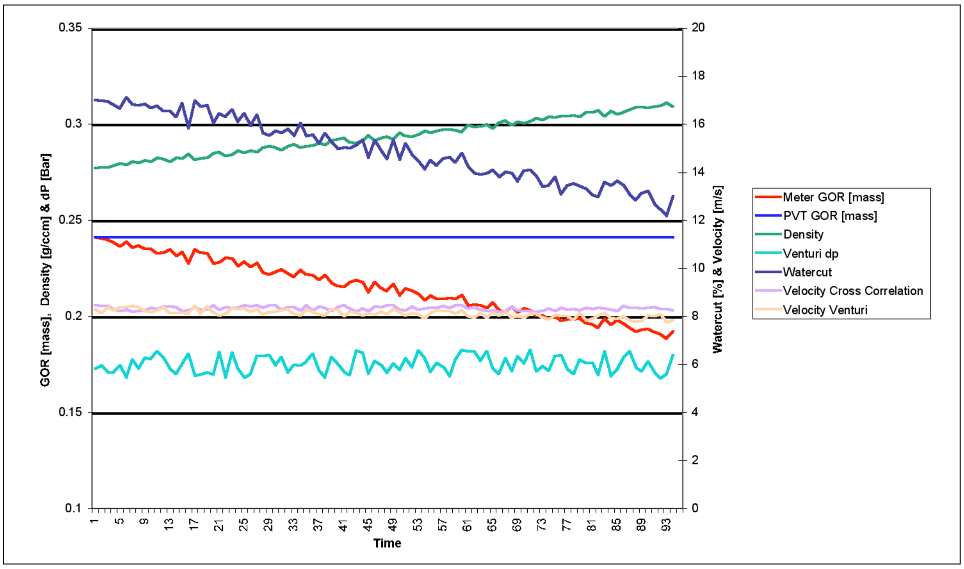
a) Measured Mass GOR (Meter GOR).
b) GOR from PVT module (PVT GOR)
c) Measured density.
d) Measured Watercut
e) Measured venturi delta pressure.
f) Velocity based on Cross-Correlation
g) Velocity based on Venturi

System alarms would typical be generated based on a discrepancy between measured GOR and PVT GOR, Cross-Correlation velocity and Venturi Velocity and finally redundant temperature, pressure and delta pressure transmitters. To identify the origin for the discrepancy, it is required to analyze the trend in the measurement data to identify potential problems.

The following examples demonstrate how failure situations can be detected and analyzed. The plots are based on simulation of raw data using the MFI simulation module. Any measurement error has gradually been introduced such that at time equals 1, no error has been introduced and at time equals 100, maximum error has been introduced. The following "failure" situations has been simulated:

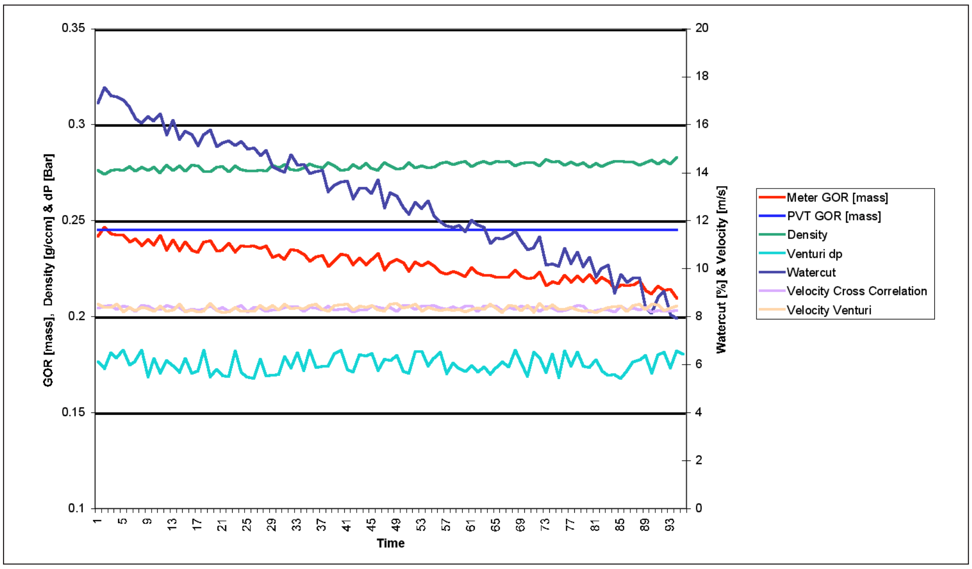
1) Error in density measurement.
2) Error in watercut measurement.
3) Compositional change of well fluids.
4) Error in venturi delta pressure measurement.
5) Internal deposits such as scale and Wax.

4.1. Error in Measured Density



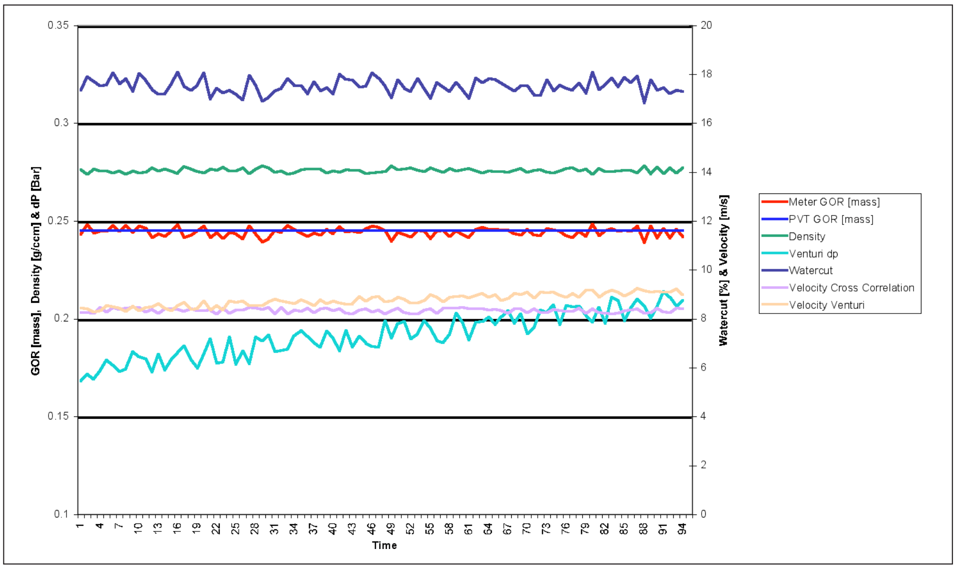
In the event of an error in the gamma densitometer, there will be an effect on the measured density. Since the measured density is wrong, it would affect the measured watercut, measured GOR (Meter GOR) and eventually the volumetric velocity from the ventruri.

4.2. Error in Measured Watercut



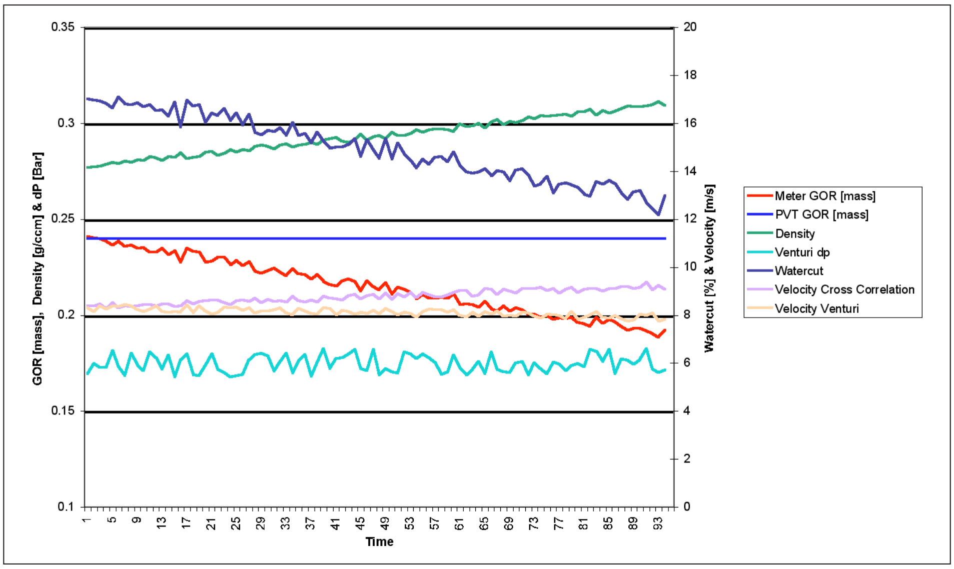
Any failure in the watercut measurement will most easily be detected by comparing the GOR based on the PVT module (PVT GOR) and the measured GOR (Meter GOR). In watercontinuous flow, a similar behavior could be an indication of a salinity change in the produced water such as at water break through in the reservoir. However, the GOR of the meter may also change due to a compositional change of the well such as a gas break-through. Therefore it may be required to verify the watercut measurement by either a sample from the well stream or by inspection of a long-term trend of the watercut in order to assess the cause for discrepancy on mass GOR.

4.3. Error in PVT Module Composition



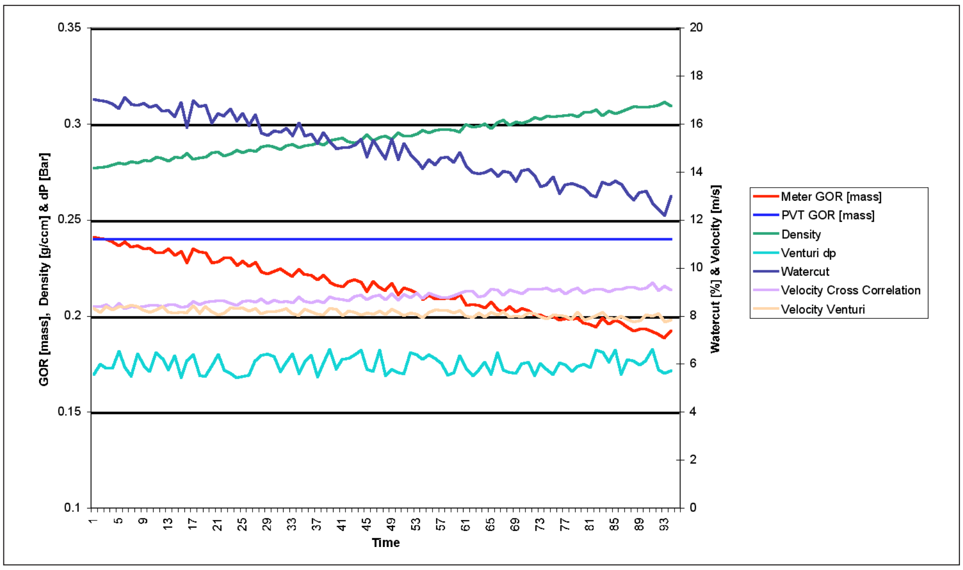
Gas break-through of the well would typical affect the composition of the hydrocarbon fraction. A compositional change of the well would most easily be detected by comparing the GOR of the meter and the PVT module. As shown above, a compositional change of the well would typical affect the mass GOR of the meter while the other measurements would be less influenced. Since the PVT module is unaware of the change in well composition, it will remain unchanged. To investigate the possibility for a well compositional change, the PVT module can be used to estimate the new well composition based on the measurements from the MFI MultiPhase Meter. An iteration process between the PVT module and the meter will then be initiated and continue until the GOR from the PVT module matches the GOR from the meter. The outcome of this iteration process would be the new hydrocarbon well composition.

4.4. Error in Venturi Delta Pressure Measurement



Deviation between the velocity measured by the venturi meter and the Cross-Correlation is an indication of an error either in the venturi meter, Cross-Correlation meter or density measurement. Since the GOR of the PVT module matches the GOR of the meter, the density measurement is most likely correct and hence indicating an error in the venturi velocity measurement. For this particular situation, there is most likely an error on the delta pressure drop across the venturi since it is not following the same trend as for the stable readings from the Cross-Correlation measurement.

4.5. Internal deposits such as Scale or Wax



Tests performed by Statoil and Rogaland Research Center has shown that the MFI MultiPhase Meter is able to measure with severe amount of scale on the inside of the sensor. However, scale and wax would affect the calibration of the meter. Above is a typical behavior of the meter in the event of scale or wax. The behavior of the venturi in the event of scale and wax is uncertain and for this particular example it is assumed to remain unaffected. In fact, the venturi may give an output velocity of zero due to plugging of delta pressure tapings, or give a very high velocity due to reduced beta ratio. However, since the behavior of the cross correlation meter is well defined whereas the venturi is uncertain, they would most likely not give the same result as demonstrated by this example.

A typical indication of scale or wax is increased density together with decreased watercut. As a result, the GOR measured by the meter would not match the GOR from the PVT module. In addition, the velocity measured by the Venturi would not match the velocity measured by the Cross-Correlation velocity meter for several reasons. First, reducing the area of the sensor would affect the calibration of the Cross-Correlation velocity meter such that it gives a too high velocity, and second, it would have an uncertain affect on the dP measurement and beta ratio of the venturi.

5. Summary

The cost benefit by using multiphase meters is according to oil field operators substantial compared towards conventional technology. MultiPhase meters have, over the past few years, shown to be reliable and give good and repeatable measurement. At present, one of the main challenges within the industry is to provide the required amount of understanding among end users related to working principles, limitations and maintenance requirements in addition to utilization of new opportunities based on real time measurements. Roxar has developed a new concept called MMS (MultiPhase Management System) to provide the end user with a tool for simplified calibration and maintenance based on Preventive Maintenance Routines (PMR) in addition to modular add-on functions to fully take advantage of large amount of “real-time” data stored in a database. The foundation for the PMR module is based on an extensive qualification program of independent velocity measurements, integration of a PVT package and the well-defined correlation between dielectric constant and density for hydrocarbon at microwave frequencies. The MMS system will be an attractive solution to manage well test and allocation data both in terms of investment and operation cost in addition to improved utilization of multiphase measurements to recover and produce more oil.

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.