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Technical Paper

Operational experience with virtual flow measurement technology

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1 Introduction

Since many years, operators have been using various multiphase and wet gas metering techniques. One of the reasons for implementing multiphase metering solutions was to replace test separator for topside and onshore applications as well as to develop subsea tie-ins by installing individual multiphase metering systems on each well. This has allowed to reduce development costs and to improve production optimization through continuous monitoring. In parallel so called virtual meters combining simple pressure & temperature measurements with flow model equations have been also evaluated and used with variable degree of success. The interest for virtual flow measurement has been re enforced recently with need to optimize metering schemes as well as to find out alternatives or complement to conventional multiphase meters (MPFM) and wet gas flow meters (WGFM) for flow determination .

This paper is describing some of results obtained so far with different virtual flow metering solutions as well as some lessons learnt from their implementation with the objective to answer to the question:

Can a virtual metering system replace a multiphase flow meter?

2 VFMS and standardisation

The concept of virtual flow measurements combining pressure sensors and model is not new . Well performance people have been using since long time uptream well head pressure to estimate rates assuming some values of BSW & GOR obtained on a regular basis from well testing using test separator .
First commercial offers came in 90 ‘ s to answer to early subsea development where estimation of liquids and gas for which well was requested for field production optimisation . At that time , subsea MPFM were not establihed. Development of multiphase flow meters with availability of subsea versions has to some extend limited the development of soft solutions like virtual meters even if virtual measurements have always been considered as a potential alternative or solution for multiphase flow determination .

First NFOGM [Ref 1] handbook on Multiphase metering has introduced virtual flow measurements as other MPFM solutions and defined them as “ advanced signal processing systems estimating phase fractions and flow rates from analysis of the time-variant signals from whatever sensor or process simulation programs combined with techniques for parameter estimation. NFOGM was indicating if pressure and temperature of an upstream or downstream location can be measured and the pipeline configuration is known along with properties of the fluids, it is then possible to make estimates of phase fractions and flow rates"

More recently API MPMS [Ref 8]came with a definition for virtual flow meters (VFM) and the ISO technical report ISO TR 12748 [Ref 2] on wet gas flow measurements mentionned the concept of Virtual Metering System indicating that a virtual metering system can be used to estimate flow rates based on various existing measurements in a production facility, like measurement of temperature, pressure, and other information like choke and valve settings, etc.,. combined with either physical models (e.g. using PVT models, pressure drop models, etc.) or mathematical process. ISO TR 12748 is also indicating " the uncertainty of the estimated flow rates is not generally well known and s VMS should not be considered as a replacement of a WGFM but rather as a complementary tool to provide backup and redundancy "

In this paper , we are using the VFMS acronym to describe Virtual Flow Metering System which can be applied to individual VFM or extended multipoints virtual metering systems for full networks.

3 Company approach for Virtual Metering Systems

VFMS interest within TOTAL company came from several needs & perspectives like :

- Providing a back up to multiphase meters especially on subsea developments
- Findong continous well metering solutions for offshore & onshore
- Evaluating low cost solutions for multiphase metering

Initiatives taken so far consisted in using / testing solutions from market but also in developping in house solutions based on reconciliation software [Ref 4 & 5] . We have introduced the concept of OFMS (Overall Flow Metering System) based on DVR for deepwater [Ref 3] developments which is a virtual metering system applied to a complete asset / network including wells , flow lines and process measurements

4 VFMS1 : subsea oil field

4.1 Application & objectives

Virtual Metering has been installed on a subsea oil field comprising 18 subsea oil wells producing from 4 different reservoirs. Each well is also equipped with a subsea MPFM located upstream of the choke valve.

Reservoir	Wells	GVF	WLR
Reservoir 1	Wells 1 to 4	56-80%	4-24%

Reservoir 2	Wells 56 to 9	~55%	0 to 30%
Reservoir 3	Wells 10 to 15	20-50%	5-50%
Reservoir 4	Wells 16 to 18	~50%	0-10%

Table 1: Well properties

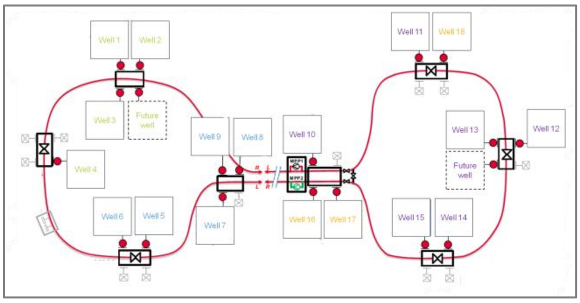


Figure 1: Subsea Field Layout

Virtual metering was implemented on each production well with the following objectives :

- Provide back-up values in case of subsea instrumentation & MPFM failure
- Estimate unmeasured parameters of the production system.
- Detect sensors failure in order to give the user the possibility to eliminate it from the reconciliation process.
- Generate alarms when deviations are detected between validated and measured data or when discrepancies are detected between measured data.

4.2 **VFMS 1 Model**

VFMS 1 is a model based application integrating P & T downhole and surface sensors as well as other differential pressure sensors.

Fluid property	Black oil data	PVT tables
Well pressure drop	VLP	Supplier model
Well temperature drop	VLP	Supplier model
Choke pressure drop	Supplier model	
Venturi model	ISO 5167	

4.3 **Calculation principle**

The wells rates are calculated at the well level .There is no balance or reconciliation of rates with topside measurements . Rates calculation are based on minimizing of an error function between calculated (X_c) and measured (X_m) data, multiplied by weighing factor W_j applied by the user.

$$Err(x) = \sum_{j=1}^{n} W_j \left(X_{m,j} - X_{c,j}\right)^2$$

If there is no weighing factor applied to the sensor: the sensor will not be used in the calculation process . If there is a low weighing factor applied to the sensor, the sensor value will be used to a certain extent in the calculation process and the final calculated value can differ from the measured one. If there is a high weighing factor applied to the sensor: the sensor value will be trusted and calculated value will not differ from the measured value.

The calculation ends if the change in the error function is below a certain limit or if the maximum iteration number is reached.

4.4 Set up of Calculation parameters

Weight factors	Fixed by user
Acceptable values	Minimum and maximum acceptable values for oil rate, WLR and GOR
Fixed WLR & GOR	WLR and GOR can be fixed
Fixed measurements	measured value of a sensor is used instead of calculated value

4.5 System initial tuning & calibration

Wells tuning was the first step taken after the installation . The tuning consists in:

- Choke calibration by correcting the choke curve to match the pressure downstream choke for subcritical flow, or match the critical flow rate for critical flow.
- Venturi calibration by adjusting the discharge coefficient,
- Pressure calibration using correction factors on linear viscosity, linear diameter, frictional pressure drop and density,
- Temperature calibration using correction factors on overall heat transfer coefficient.
- Adjusting the weights on the different sensors as well as on GOR & WLR when they have been used in the VFMS

Tuning of the choke and venturi models is performed against the MPFM measured rates. Calibration was done on simulation mode against historical data. Once the simulation result was found satisfactory the calibration parameters were exported to the online mode.

4.6 Operation

Tests were conducted during 4 months in order to :

- Validate and confirm MPFM readings using KPI for each well and each phase established as follow:

$$\mathrm{KPI} = \frac{\text{VFMS Calculated Flow Rate}}{\text{MPFM Measured Flow Rate}}$$

- Check the capacity of the VFMS to recalculate flow rates for oil, water and gas in case of loss of MPFM raw data (WLR information , GOR, venturi DP).
- Evaluate the robustness and autonomy of VFMS 1 over time in terms of need for recalibration or tuning

4.7 Flow rate calculations

For 16 wells , VFMS is capable of calculating oil , water & gas rates which are consistent with MPFM readings (+/- 10 % deviation) once the wells are properly tuned with sensor.
For 2 wells out of the 18 , WLR and GOR information were required

Well	Oil	Gas	Water	Well	Oil	Gas	Water
1	0.99	0.97	0.99	**10**	0	0	0
2	1	0.96	1	**11**	1.03	1.13	1.03
3	0.99	0.99	0.99	**12**	0.79	1.24	0.79
4	0.98	1.03	0.98	**13**	1	1	1.03
5	0.99	0.97	0.99	**14**	1	0.98	1
6	1.01	1.01	0.93	**15**	1.11	1.11	0.90
7	0.94	1.07	0.94	**16**	1.28	0.63	1.28
8	0.91	0.95	0	**17**	0.94	0.94	0
9	1.02	1.01	1.01	**18**	1	0.97	1

Table 2: Oil, Gas and water KPIs during the test

4.8 System stability

Behaviour versus time was investigated by tuning 15 wells out of the 18 wells of the field. Once the tuning parameters were exported to the online mode, the stability of the KPIs was followed, and a new tuning was initiated in case of deviation higher than + / -10%.
Over 2 month , 8 wells out of 15 required a re-tuning after a change in the operating conditions.
Example of well 11 is shown in Figure 2: following an increase of choke opening from 55 to 58% on November 1st, the oil KPI (red curve) increased by 4.5%, the gas KPI by 8% (green curve).
On November 4th the choke was opened to 68% and the gas KPI increased by another 37%, reaching 1.45.

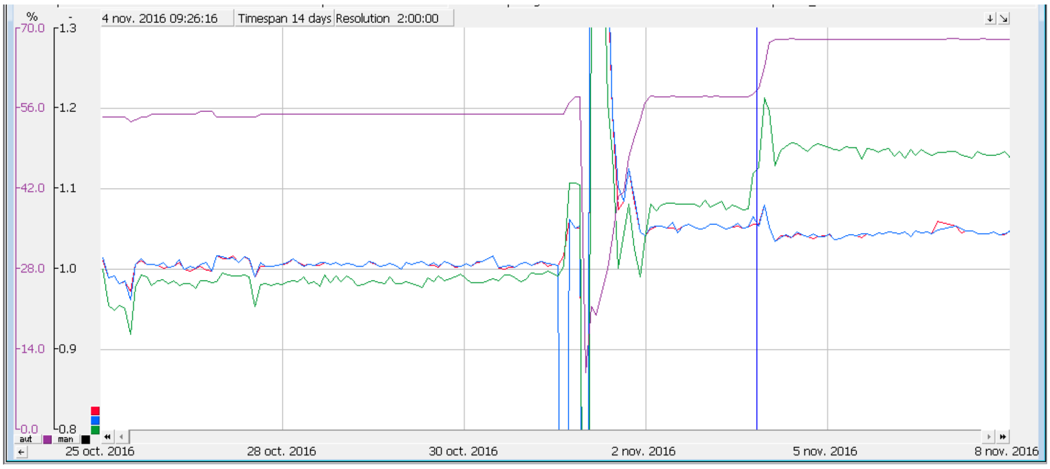


Figure 2 – Well 11 KPIs following a choke opening

An efficient tuning of each well would require a choke and venturi calibration over a large set of operating flow rates. If production data is not available at such a large range at the tuning time, wells tuning will have to be adjusted at each significant change in the flowing conditions.

4.9 Recalculation of rate in case of loss of MPFM data

4.9.1 Simulation of loss of gamma-ray data

The VFMS succeeds in recalculating the flow rates in case of loss of WLR and GOR information only if their range is sufficiently narrow to allow the model to find a unique solution.
Figure 3 shows the example of well 15 for which no weight on GOR or WLR was applied, but the maximum possible value for WLR was fixed at 55%. The measured WC value varied between 53 and 55%. The calculated oil rate (in red) is a good match with the measured value (in blue).

Figure 4 shows the calculated oil rate (in red) for a maximum WLR value fixed at 70%. The system fails in calculating correct GOR and WLR values and highly overestimates the water rate.

Figure 3: Calculated oil rate, max WLR 55%

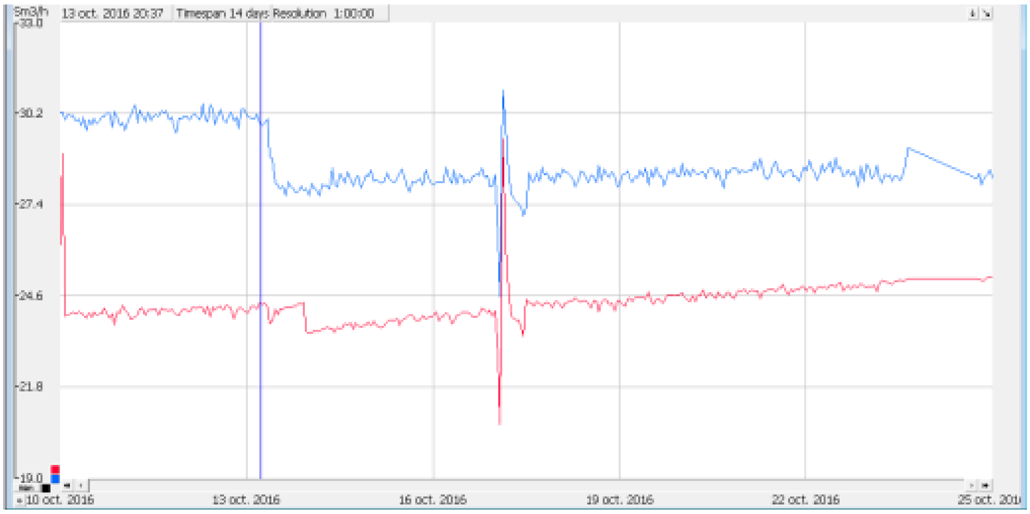
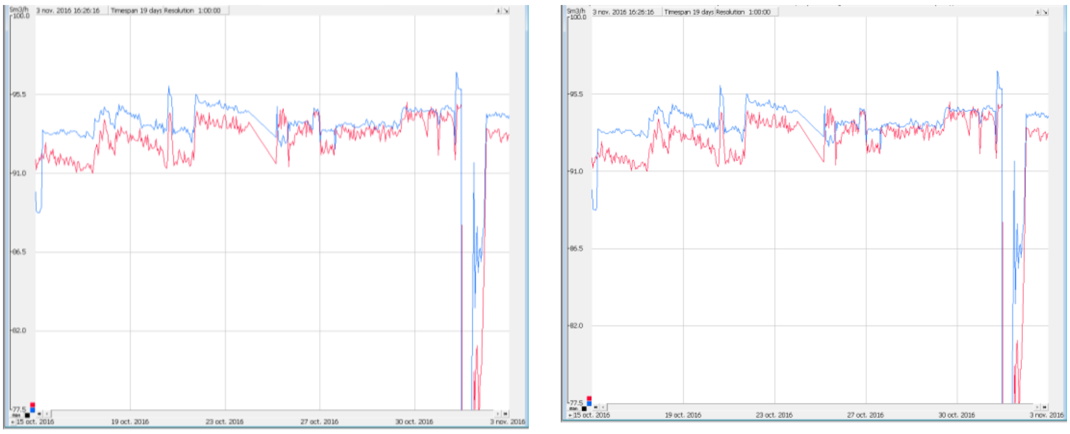


Figure 4: Calculated oil rate, max WLR 70%

4.9.2 Simulation of loss of DP across venturi

The system is able to provide a relatively acceptable estimation of the rates without differential pressure meaurement across Venturi provided the user is increasing weights on choke model and well model.
Figure 5 shows the example of well 11, for which venturi DP was not used . By increasing weight on choke model, the system calculates the flow rate with a similar accuracy than with the venturi data.



(a) (b)

Figure 5: oil rate with (a) and without (b) venturi data

5 VFMS 2 : subsea gas field

5.1 **Application & objectives**

Virtual metering has been implemented in 2 gas condensate fields located on the Norwegian Continental shelf. They are producing to a platform through a satellite system C.
The water depth of all 3 systems is around 120 meters. Figure 6 provides an overview of the A, B and C subsea configuration.

The satellite system C is located at 16 km east of the receiving platform.

The field B is located at 24 km east of the receiving platform.

Both satellite systems are connected to a 12" production flowline.

Field A is a standalone satellite well development with 7 km tie-back to C via a 236,5mm ID (9.3") pipeline.

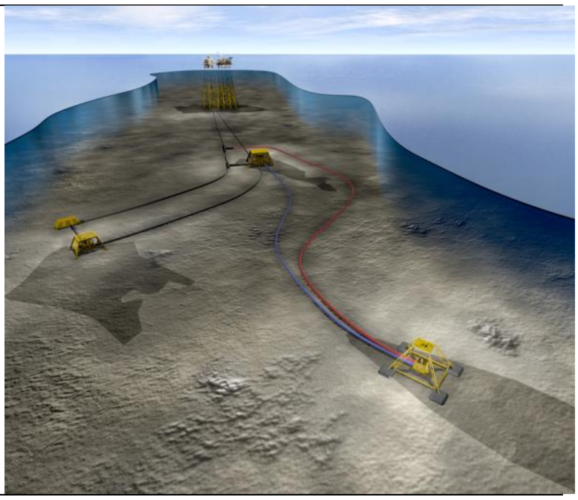


Figure 6 Scheme of the field

In that case , no MPFM or WGFM has been installed basically for cost reductions and VFMS use objectives were :

- to give an estimation of well production rates
- to split for allocation production between Field A and B based on the virtual meter estimation

5.2 Design

The virtual flow meter system uses simulator a dynamic simulator embedding flow models & fluid models to estimate the flows for the respective wells based on relevant real-time parameters (Pressure, temperature, valve opening…) while performing mass balance and back-calculation
The dynamic simulator will match the measurements given by the instruments within the system.
It is important to note that the well virtual data haven't been used directly in that application . Focus has been put to calculating a split key in percentage between Field A and B based on the virtual meter estimation to share the production between both fields. As such imbalances are equally shared between both fields and allocated masses are consistent .

5.3 Calculation & dynamic reconciliation

The primary tool calculating the split key consists of a dynamic model of the A and B fields subsea facilities along with parts of the production and processing system at the receiving platform relevant for the model boundaries.
The module will calculate the split based on a pressure, temperatures and flow measurements within the system.

This module reflects the uncertainty from the input source data as well as a flow weighted uncertainty split when calculating the result.

The real time online system will be used for the daily reporting and the allocation will be performed at the end of the month.

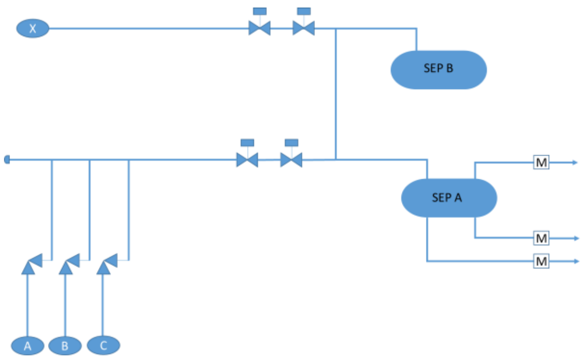


Figure 7 Simplified process diagram

VFMS methodology is based on a dynamic model running in parallel with the process. The model receives all control and operator inputs such as set points, on/off signals, opening and closing of block valves etc.
These inputs, called synchronizing signals, will be used in the model at the same time as it is performed on the plant. The model and the real plant will then synchronously follow each other during transients.
The dynamic model is using the plant measurements to prevent the model from drifting away from the plant.

5.4 Operation : system tracking for performance monitoring

The VFMS system performance tracking tests indicates how good the simulation model matches the measurements.
The score is high if the model follows the measurement. When it drops to a low value it means that some of the measurements are faulty and/or the model needs to be calibrated since critical parameters in the plant has changed. It is calculated from:

$$Performance = 102.5 - 7.5\sqrt{\frac{\sum Wi(Xi{,}model - Xi{,}measured)^2}{\sigma i^2}}$$

Where Wi is the configured weighting factor, Xi is model and measured value, σi is the configured standard deviation and N is the number of measurements.

The equation is designed to give a value of 95 when all measurements have a deviation equal to the configured standard deviation.
A low performance value suggests that some of the plant instruments and/or the simulator need to be calibrated.

The performance indicators are designed to indicate the performance during production. Consequently, the system performance tracking indicator may be poor during periods with no production. This must be taken into consideration when evaluating the performance.

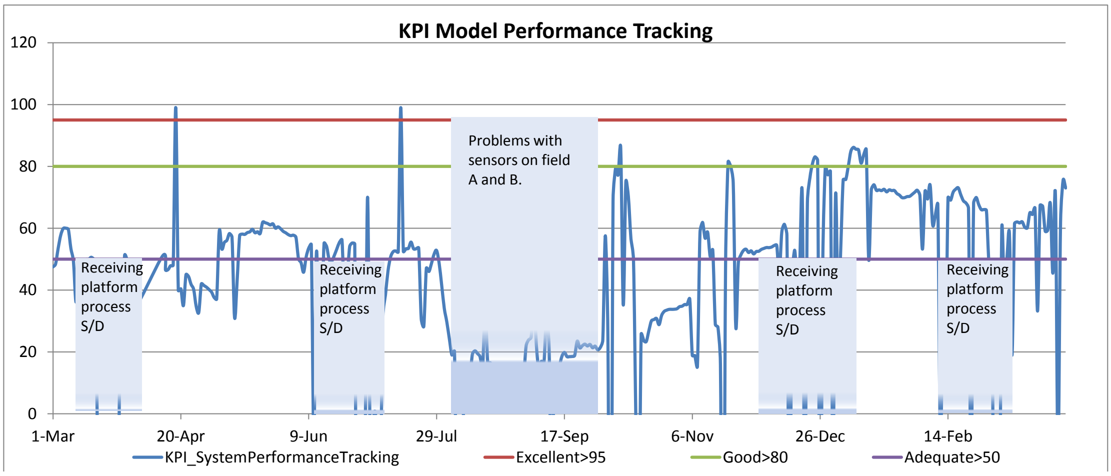


Figure 8 Performance tracking

As shown in the graph above, the performance of the system has been considered as at least adequate for most of the time. However, upsets in the receiving facilities process or malfunctioning sensors have of course an impact on the performance of the system.

5.5 Results & findings

5.5.1 Performance targets

The performance of the simulator was analyzed in terms of the targeted deviation:
Flow ±10%
Temperature ±5°C
Pressure ±10%.The monthly mass estimation should be for commingled gas ± 10% and for commingled condensate ± 10 %.

5.5.2 Gas flow rate

The following graph shows the accumulated and measured mass values for the gas rate downstream the inlet separator.
This graph shows good consistency between the measured and estimated values .The accumulated gas deviation has been within the acceptable parameters (+/- 10% deviation).

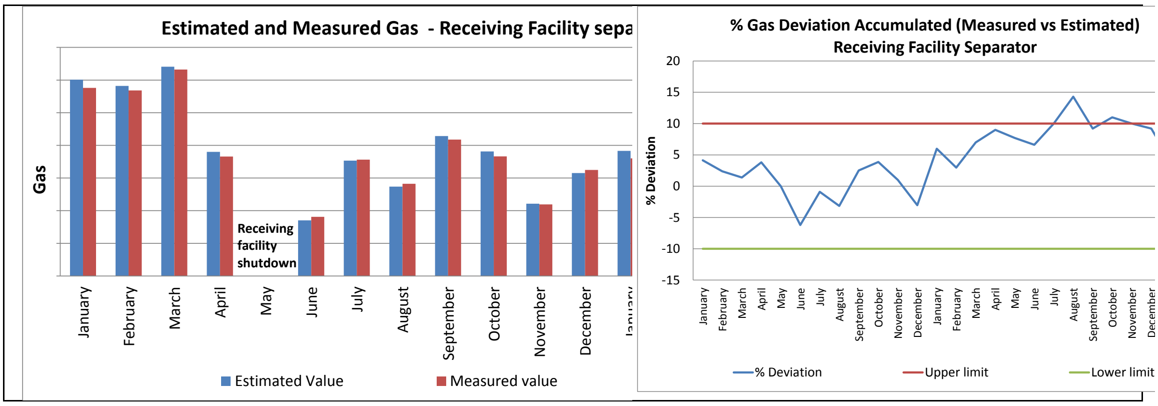


Figure 9 & 10 Estimated/ Measured gas & deviations

5.5.3 Condensate mass rates

Figure 11 shows the accumulated and measured values for the condensate ratess downstream the inlet separator.
The difference between the measured and estimated values is slightly higher than for the gas phase, however, it remains reasonable and consistent.

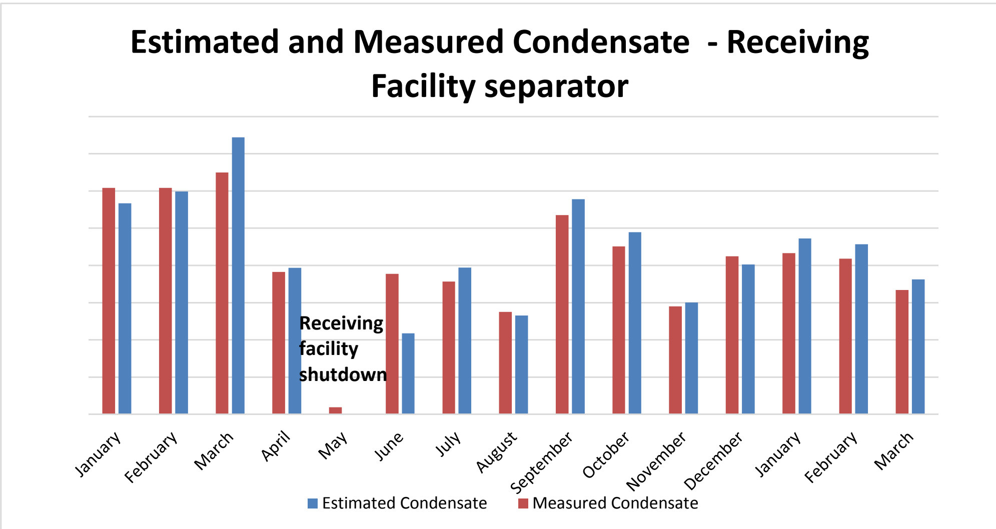


Figure 11 Estimated & Measured condensate mass flow

5.5.4 Pressure calculations upstream choke

- Field A

The following figure shows the instantaneous percentage deviation between the pressure measured upstream choke and the estimated value from the simulator. This graph indicates an acceptable deviation within the ±10% acceptance accuracy between the estimated value from the simulator and the measured value by the instrument. There are some values out of range but these mainly correspond with shutdowns on receiving facilities. The virtual meter does not have a reservoir simulator and is not able to reproduce a pressure build up mechanism.

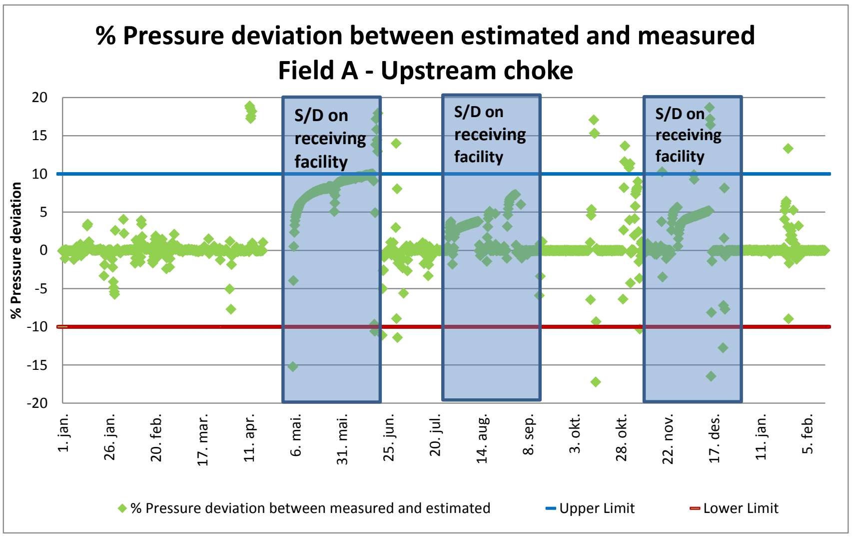


Figure 12 Field A - % of pressure deviation - upstream choke

- Field B

Deviation between the estimated value from the simulator and the measured value are within the acceptable accuracy of ±10%. Values found out of range mainly correspond with shutdowns on the receiving facilities.

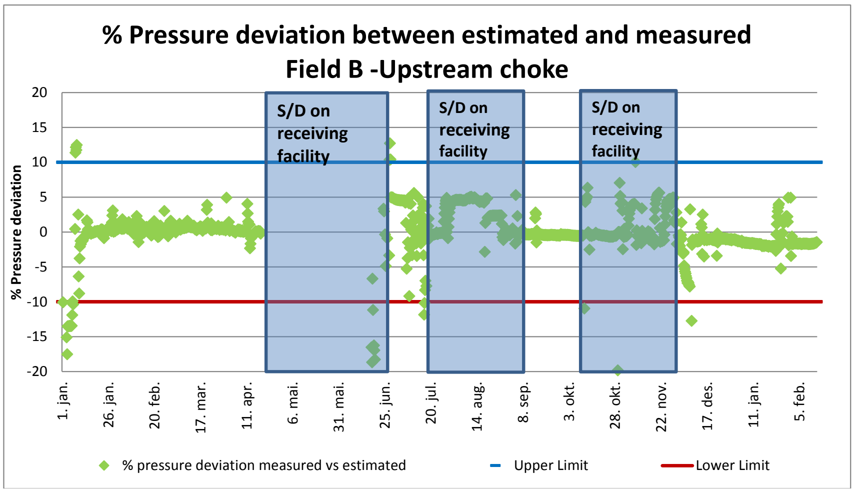


Figure 13 Field B - % of pressure deviation - upstream choke

5.5.5 Temperature calculation upstream choke

The following graph shows the difference in the temperature upstream choke between the measured value and the estimated value from the simulator. It indicates a deviation above the acceptable accuracy ±5°C between the estimated value from the simulator and the measured value. This temperature transmitter was manually suppressed due to the big deviation and inconsistencies with the temperature measured downstream the choke. Hence, this transmitter has no influence on the temperature target for the field B.

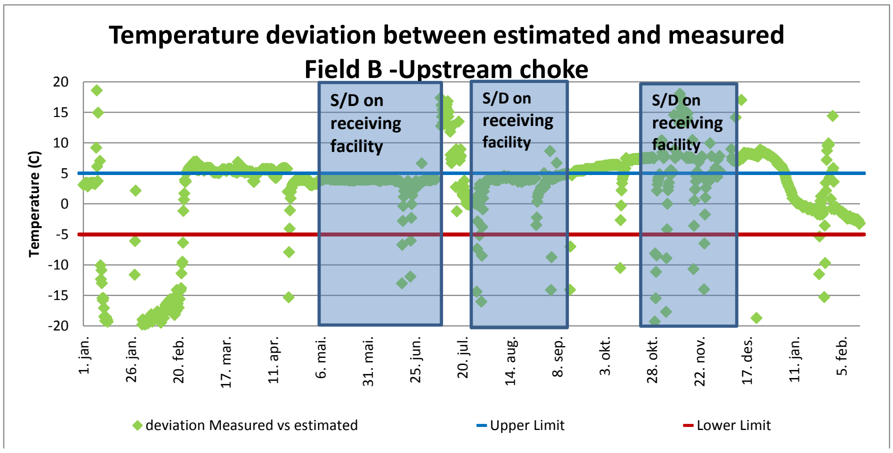


Figure 14 Field B - Temperature deviation - upstream choke

5.6 Representative fluid samples

Availability of representative fluid samples was the main operational challenge. During the first year only one representative fluid sample for the field B was taken during a shutdown of field A but independent samples for each well cannot be taken without dramatically impacting the production.
Estimated field B and A compositions have been developed using a process simulator by using samples of the combined fluids topsides.
However, it shall be noted that the challenges with obtaining representative fluid samples would also have affected the performance of a multiphase flowmeter.

5.7 Data availability / re-run mode

Virtual meter has required a permanent connection to the real time monitoring system from the field. From time-to-time, the real time connection was failing, and the simulator did not receive any data. A re-run functionality allowed to rerun the relevant time period from the latest snapshot available in the s\system after the date was populated. This was proven to be very useful.

6 VFMS 3 : offshore oil fields

6.1 Virtual metering based on data reconciliation software

VMS solutions can be developped combining DVR (Data Validation & Reconciliation) software from market with in house flow models . Such DVR based VFMS have been used both for subsea flow measurement but also for topside meaurements [Ref 4 & Ref 5]

Specific DVR model of the installation including streams, sensors and flow meters, flow lines, connections, process equipments like pumps, separators, valves, etc. has been built .Models are incorporating sensor uncertainty as well as VLP (Vertical Lift Performance) tables giving relationship between pressures and flow rates, heat transfer correlations etc. Specific fluid properties and compositions are associated to each stream.

6.2 Topside application

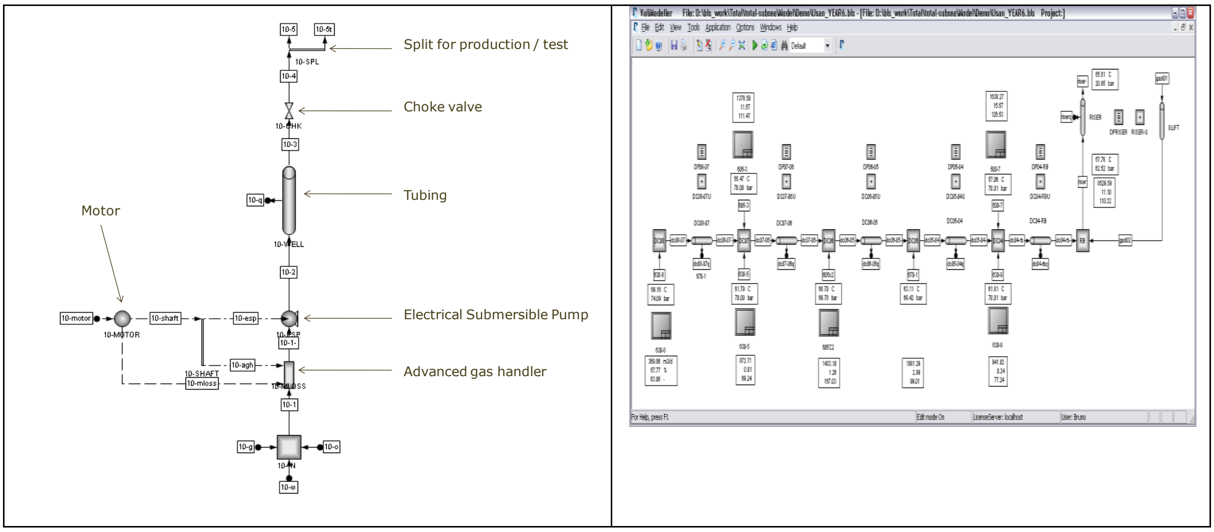
DVR based VFMS has been installed on an offshore field in the Middle East with 16 wells: 10 are connected to a main platform, 4 to a first satellite and 2 to a second satellite. Topside MPFM are available on the main platform and on one satellite for testing individual wells periodically.

The main objectives of this application were to:

- Limit oil production losses by avoiding production deferment due to well test of commingled wells
- Secure investment in instrumentation
- Provide backup values for the MPFM used for testing
- Provide continuous production well values between testing.

6.3 Design

Example of topside well models as well of subsea network models can be seen below.

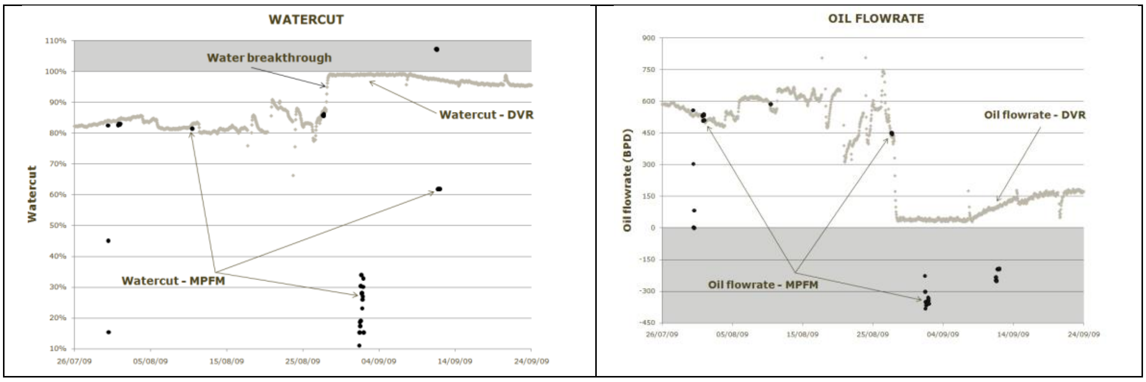


6.4 Implementation

Once the model is developed and preliminary accepted, the model is installed and is connected to a real time historian data base.

6.5 Results

The DVR based VMS system provides consistent oil and water flow rates for each individual well. In the following figures , validated and reconciled values for both water cut (top figure) and the oil flow rate (bottom figure) are represented . This is compared to the value of the MPFM that are sporadic as the MPFM is used for testing only.



7 Lessons regarding VFMS operation

The overall experience of operating a virtual flow metering system on real field applications has shown positive points and weaknesses . VFMS can anwer to a variety of applications from MPFM back up to alternative to rate estimation .

Virtual metering can be used as a low cost solution in a subsea system with gas estimation in criteria +/- 10% . Condensate residual is not always within acceptance criteria of +/- 10%. On oil fields , +/- 15 % has been achieved on rates after tuning without major change in operating conditions (choke ..)

A VFMS system using minimum well instrumentation (well pressure and temperature, choke DP, venturi DP) is not sufficient to obtain reliable oil , gas & water flow rates on a long term (> 2 months). Full alternative to MPFM or WGFM requires models regularly updated as well as additional sensors or informations like BSW or GOR .

Today performance of the VFMS are less than the quoted performance of multiphase flowmeters . An additional instrumentation providing WLR or GOR information is recommended

Robust flow models valid if conditions are changing are needed : a choke model changing versus rate is a weak point . There are frequent needs for recalibration and tuning : changes in the operating parameters often require a choke recalibration or a complete retuning of the well. All VMS require either a MPFM or a separator with flow meters for tuning / calibration.

VFMS system maintenance is time consuming for large fields with several wells.
The calibration are specific to each and every well: there is no “template” tuning for wells even the ones from the same reservoirs and using the same PVTs.
Tuning robustness is questionable : Wells with similar tuning can give completely different results .

Operation of VFMS requires significant involment of skilled specialists: one / two hour per day for 15 wells .Up to now , the market is offering virtual flow meters rather difficult to operate & understand by users (supplier models , weight factors ..) .DVR may offer flexibility to use in house models as well as to use uncertianty of sensors as well as specific sensors .

DVR based VFMS implementations on oil & gas production fields have been providing , on a continuous basis, an improved set of measured and well calculated data with reduced uncertainties. DVR Flow reconciliation brings redundancy and can be used to detect measurement errors and identify faulty sensors on a continuous basis.
In any type of VFMS , maintenance of sensors is essential as results depend on the quality of inputs and transmitters.

8 Conclusions and way forward

In the current climate of cost optimisation , Virtual flow metering system VFMS are offering an alternative to conventional MPFM & WGFM for specific metering & allocation applications.Larger acceptance of VFMS may be obtained through introduction in new ISO TR 21354 [Ref 7] dealing with multiphase measurements.

They are using simple sensors rather than costly hardware or gamma sensors which is definetely a must, but of course compared to some MPFM or WGFM uncertainty may be higher .

But experiences gained so far indicate that in all VFMS systems tuning & calibration requiring reference measurements are mandatory as well as fluid property knowledge .

If VFMS are cost effective solutions regarding CAPEX compared to MPFM , they are associated with significant OPEX because they require significant follow up .

They also require skilled people which competences are not easily found in Operation assets .This has up to now limited the development of VFMS to very specific cases .

Improvement of uncertainty is possible through more robust models and calculations associated to continuous follow up [Ref 6] using remote metering monitoring (RMM) by Operators

Acknowledgement

The Authors would like to thank Eldar Khabibullin from TOTAL Norge for contribution to collect data for some VMS field experiences.

Abbreviations

VFMS: Virtual Flow Metering System
MPFM: Multiphase Flow Meter
WGFM: Wet Gas Flow Meter
VFM: Virtual Flow Meter
VMS: Virtual Metering System
OFMS: Overall Flow Metering System

DVR: Data Validation & Reconciliation
RMM: Remote Metering Monitoring

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