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Multiphase Flow Metering-A Case Study from Badra Oil Field

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Abstract

This paper presents the full cycle project experience for the implementation of multiphase flow meters at the Badra Oil field at the well head and production lines, including a discussion of the design and selection criteria and a detailed description of flow loop proving, commissioning and on-going validation and tune up procedures. In addition, results of further research based on field data is presented including a study of the potential of neural nets for transfer learning and automated malfunction detection.

Introduction

Badra Oil Field situated in the Wasit Province in Eastern Iraq and operated by Gazprom is estimated to hold reserves of over 9 billion barrels. Current production rates of 22 wells vary from 1000 bbl/d upto 13000 bbl/d.

Badra Oil Field production facility design envisaged inline multiphase flow meters at each well head and at each production train. The principal criteria for selection of inline MPFMs was the sustainability of the system in view of the highly corrosive fluids and the sustainability of the accuracy in view of changing flow conditions. There were a number of competing MPFM technologies to choose from when the project kicked off in 2013 – first MPFM installed in August 2014 (Fig. 1). Here is a cursory review of the state-of-the art of MPFM technologies at the time—fair to say that there has been no quantum leap since then [1,2].

Early research into MPFMs were led in the 90s by physicists and instrumentation engineers who tried developing innovative (and in some cases complex & fragile) sensors and signal processing technologies tailored for multiphase flow. Of the many devices developed, those which respond to composition - phase (gamma ray absorption) and water cut (microwave and infrared absorption) – were relatively successful and have survived. A number of devices which were devised specifically for measuring flow rate (eg cross correlation, magnetic resonance, imaging techniques of various kinds) did not live up to expectations and were gradually displaced by the conventional differential pressure devices (venturi and similar) of the type selected for implementation at Badra – trade mark ESMER MPFM manufactured by Petroleum Software Ltd, co-authors of the present paper.



Figure 1—ESMER MPFMs at the Well Head and the Production Line at Badra Oil Field.

Accuracy (claim and proof) remains as the bugbear of the multiphase metering industry. In early 2000s when the MPFM technologies were said to be maturing, the accuracy expectation settled to 5-10% by mutual consent between vendors and customers despite the fact that theoretical limits of uncertainty derived from elementary equations of energy and mass conservation through a differential device showed an exponentially deteriorating trend above 80% GVF - a popular region for multiphase flow in oil production lines (Fig. 2) [3]. Besides, proof of such accuracy could not be validated in a multiphase loop where the standard deviation of fluctuations is also of the order of 5-10% - due to natural turbulence in multiphase flow.

API provided some relief to the flow loop test stress (suffered by supplier and customer alike) in its guideline API 2566 State of the Art Multiphase Metering where it was said that "For all multiphase measurement systems, including types II and III, the final calibration of the system is part of the field commissioning activity" [4]. Hence, in compliance with API recommendation, the supply scope for the Badra project included the provision of a mobile separator and the implementation of a routine procedure and method for its use for the validation and recalibration of ESMER MPFMs in the field. The facility has also enabled the establishment of a field laboratory at Badra and paved the way for the R&D section of the present paper.

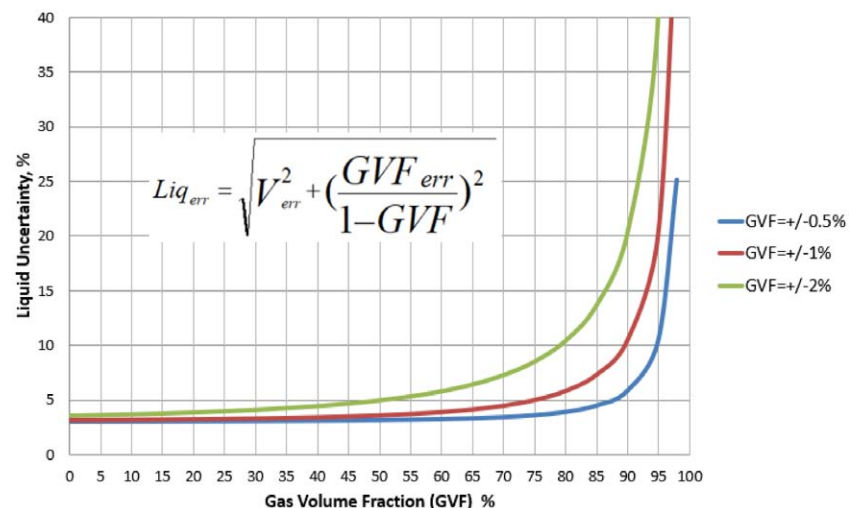


Figure 2—Multiphase Metering – Limits of Accuracy. Example showing the case where differential device (total volumetric flow) accuracy is assumed to be 3%

MPFM Technology & Implementation Scheme

ESMER MPFM field unit is a horizontal pipe comprising a set of industry standard transmitters for differential pressure measurement (through a cone), capacitance transmitter and Weatherford Red Eye insertion probe (Fig. 3). Signals are digitised at a high frequency and processed (converted to flow rates of individual phases) on a PC. Flow rates are displayed and saved on the PC and transmitted to the company network. A noteworthy feature of ESMER field unit design is that it does not require the dead T element commonly found on a number of competing systems avoiding extra pressure drop and blockage.

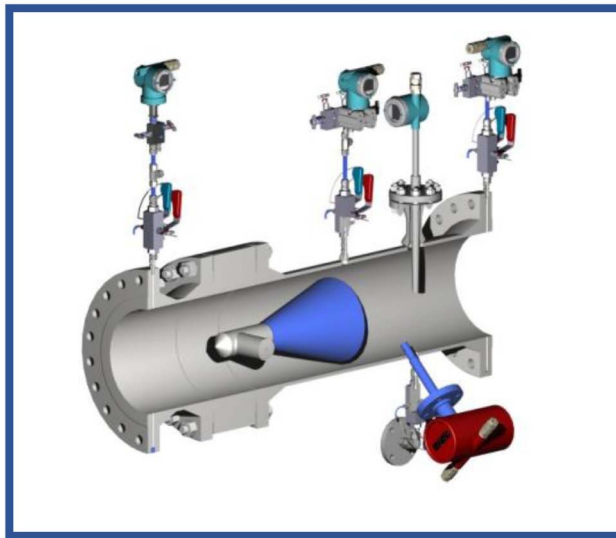


Figure 3—ESMER MPFM Schematic.

Like all flow meters ESMER MPFM requires three stages of calibration: Theoretical calibration, flow loop calibration and field adjustment (tune up). The mathematical model and its software implementation is conceived with a view to facilitating field adjustment.

ESMER MPFM's *theoretical calibration* is founded on **hydrodynamic** (Bernoulli equation) and **thermodynamic models** (EOS). The mathematical model runs on the PC concurrently in real time based on digitised transmitter inputs. Bernoulli equation predicts total mass rate assuming homogeneous flow. The EOS based on the reservoir fluid composition predicts the fluid property parameters by performing a flash calculation at actual conditions and STP assuming thermodynamic equilibrium. The output from the EOS (GVF and phase densities) are passed to the Bernoulli equation.

The main objective of the *flow loop calibration* (carried out at NEL) was to characterise the Coefficient of Discharge (CD) of the cone under multiphase flow conditions (flow regime and velocity effects) [5] (Fig. 4).

Field calibration was carried out against flow rate measurements carried out at the well head by means of the mobile test separator and analysis of liquid and gas samples drawn from the liquid and gas legs of the separator. Each MPFM is validated and tuned up individually periodically. Fluids are passed through the MFPM and the separator in line for a duration of several hours when the signals / measurements from all transmitters (MFPM and separator) are recorded simultaneously at high frequency. PVT properties of liquid and gas samples drawn from the separator are analysed at the same time. The coefficient of discharge (basic property of the Bernoulli equation) and the fluid composition (basic property of the flash calculation) are tuned up concurrently so that the online flow rate prediction by the integrated hydro-thermodynamic model running on the PC matches the individual phase flow rates measured by the separator (Fig.5) [6].

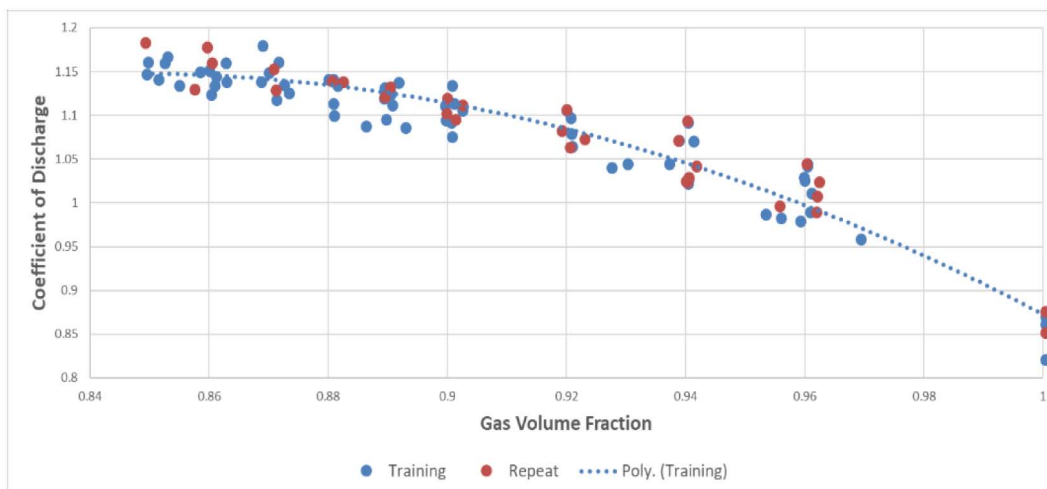


Figure 4—Flow Loop Calibration of the MPFM – Coefficient of Discharge.

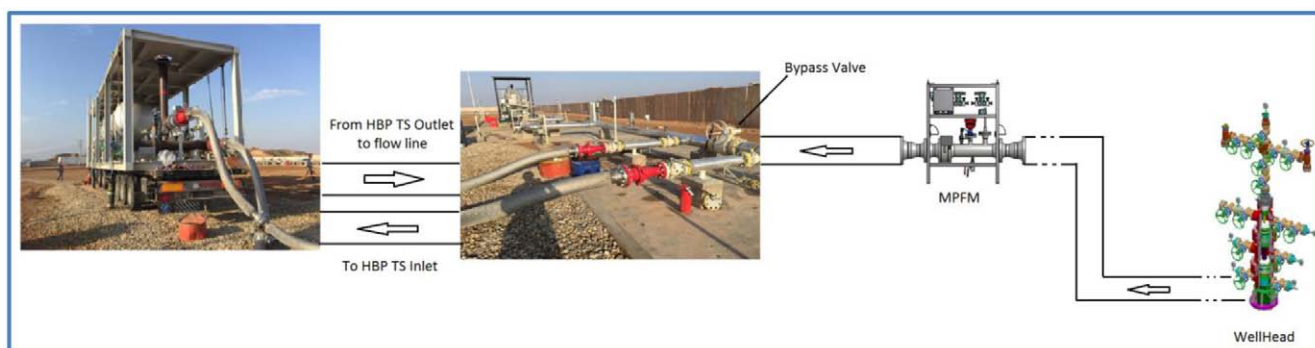


Figure 5—Field validation and tune up - MPFM and mobile separator in series.

Why Tune Up?

We've seen that API recommends validation / tune-up of MPFMs against field references. Benefits of doing so are evident logically and proven by the present experience, but what if it is not practical / cost effective to provide such reference? Or, in other words, why tune-up and what's the consequence if it can't be done (due to cost / technology constraints).

There are four issues to deal with in flow metering; "*off-set*" (also known as "accuracy"), "*drift*", "*resolution*" (overlaps with accuracy and repeatability) and "*repeatability*".

Tune up provides an effective cure for off-set and drift. In the absence of drift – not a realistic expectation -, it would be sufficient to quantify off-set during commissioning and there would be no need for periodic tune up. Tune up is of little help to improving resolution or repeatability.

Causes of drift by pipe and transmitter contamination and malfunctions can also be eliminated by cleaning or replacement of transmitters. However, such actions can also be time and energy consuming and it might be more expedient to tune up.

Change in flow and fluid properties can also cause a change in "off-set". Typically, water breakthrough is one such event. Upon detecting water breakthrough – one of the important functions of the MPFM - a calibration tune up would be necessary as water will exert a strong effect on the hydro-thermodynamic properties of the fluid.

When / How Tune Up?

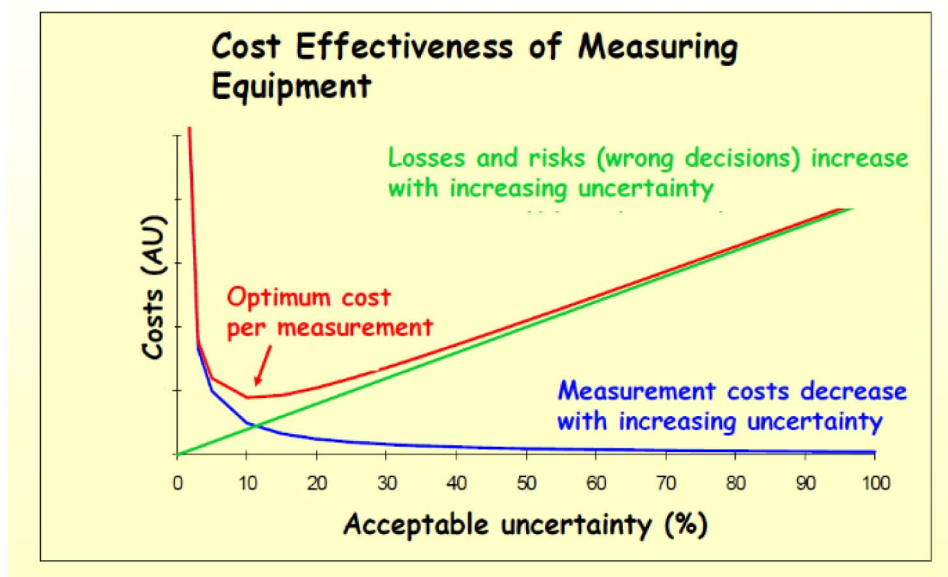


Figure 6—Optimum Uncertainty for Field Calibration [3].

Economic criteria for tune up can be represented by cost / benefit analysis. Basically, the operator will aim to minimise the sum of the costs incurred in reducing uncertainty and the "carry cost" of uncertainty. Both parameters can be represented as functions of Cost vs Uncertainty as shown in Figure 6. To put it simply, reducing uncertainty is good but comes at the expense of higher operating cost. An optimum is reached at some point. Analysis of Badra field data after three years of tune up experience (ie frequency of tune up vs uncertainty—blue curve in Fig. 6) can be the subject of another paper.

A pragmatic approach is to determine a threshold for maximum uncertainty that can be tolerated / achievable as a matter of gut feeling (operator heuristics) and turn it into a company policy (irrespective of the economic analysis). This appeared to be the case at Badra. The operators aimed to keep "accuracy" within 5% for the liquid phase and 10% for the gas phase – a realistic objective. MPFMs were tuned up if threshold breach was detected by self-test and/or external observation. To be more systematic, we can break down the detection and cure procedure into two separate activities

– ***Keeping a routine watch for detecting error breach and identifying the cause of the breach.*** This is performed simultaneously and independently by MPFM self-test and by external observation (unusual movement in the cross-correlation between MPFM signals and external online transmitters).

MPFM self-test (auto detection of malfunction) is work under construction as reported further down in this paper.

External observation is performed daily by the operators. Typical example would be the incident when the operator observed no change in choke setting/pressure, yet MPFM flow rate was increasing - attributed to reduction in cone beta due to contamination.

– ***Identifying the cause of drift and updating the calibration after examination of tune up data.*** For example, in one instance an MPFM was pulled in for tune up after negative routine watch signal. Tune up analysis revealed that the coefficient of discharge was out of norm (in comparison with flow loop and past field behaviour for which a database is kept and systematically updated (Fig.7). MPFM was taken down for inspection when it was found that the cone was blocked by debris resulting from an earlier pipe wash action. Tune up was repeated after cleaning out. It is worth noting that a deposit layer of half a millimetre could cause an error of 2% in flow rate measurement (calculation based on 6" MPFM with beta 0.7 cone).

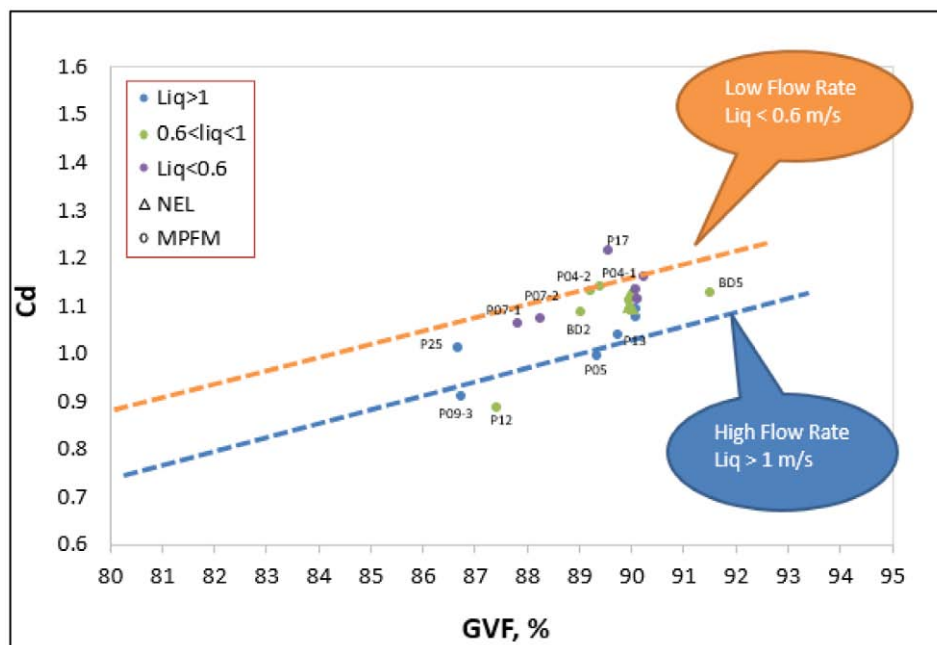


Figure 7—Characterisation of the Coefficient of Discharge

Field Implementation

Calibration Tune Up

An overview of the procedure was given above. The specific sequence of actions in the tune up cycle are:

TuneUp Well Test: Data is logged simultaneously from the MPFM and the Separator on a minute by minute basis for the duration of two hours. Liquid and gas samples drawn from the test separator are subjected to PVT analysis.

Calibration Update: Vendor runs Tune Up (MPFM) Simulator which outputs an updated calibration file. The file is transmitted by e-mail and installed on the MPFM by the operator.

Validation Well Test : Operator repeats the well test to validate the updated calibration.

It is important to note that the test separator imposes a back pressure and changes the normal operating conditions of the MPFM. The additional pressure loss (ie increase in back pressure at the MPFM) due to the separator is around 5 bar at maximum flow rate. The effects of the pressure change on fluid properties and gas volume fraction are taken into account automatically by the MPFM online (and in the TuneUp Simulator) via the thermodynamic model.

For example, the back pressure effect occurred from separator test performed on 28/05/2018 from 9:20 to 11:30 on the MPFM P25 is shown in Figure 8. The effect of separator on P, T, DP, DP/RDP (recovery fraction) and GVF are in line with expectations. In particular, the strong correlation between the recovery fraction and GVF is noteworthy (one of the methods by which ESMER MPFM corroborates the GVF prediction by the EOS model)

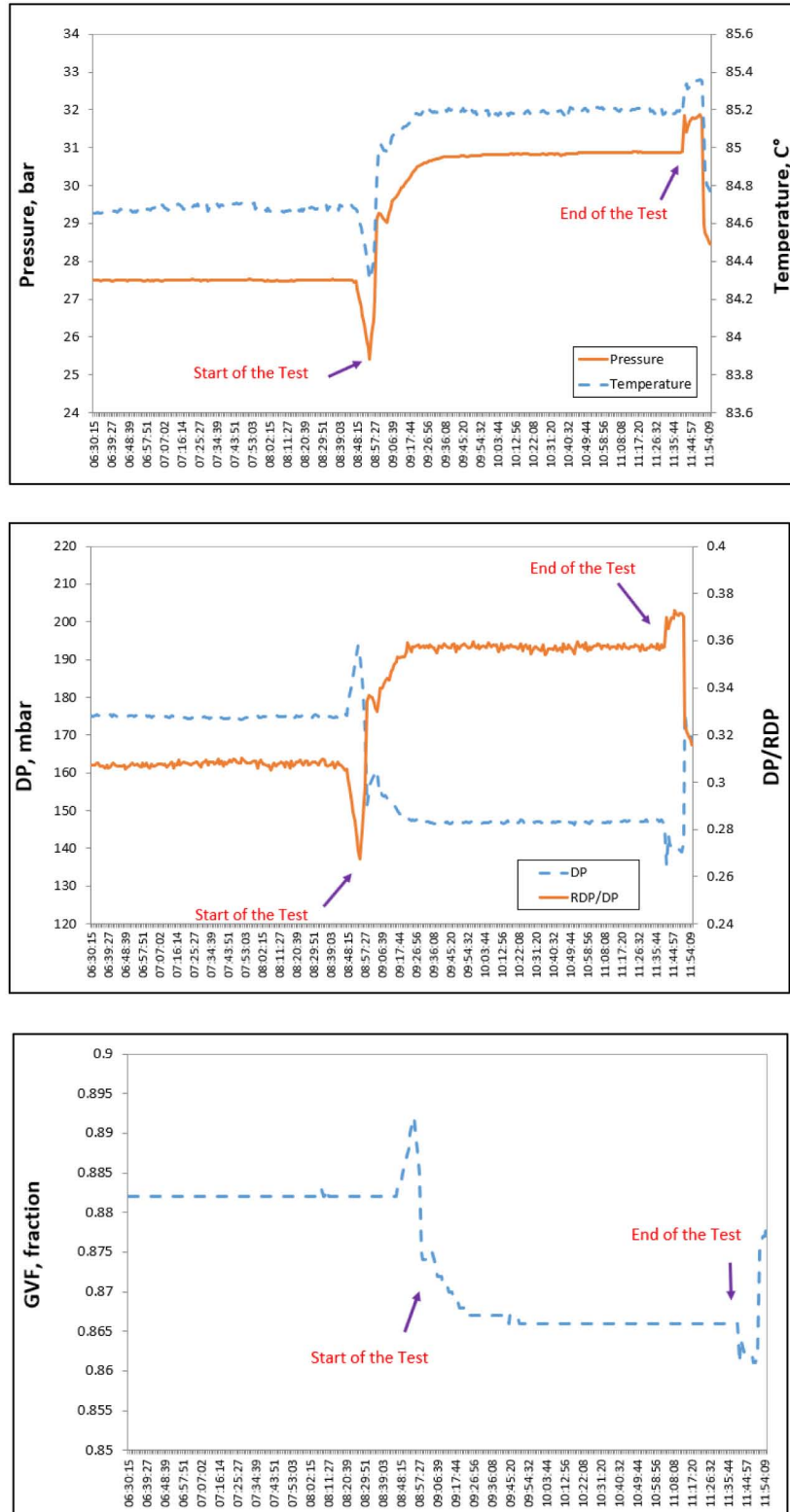


Figure 8—The back pressure effects of the Test Separator on the MPFM P25.

Figures 9 shows the oil and gas flow rates during the Tune Up Well Test performed on 28/05/2018 at MPFM P25.

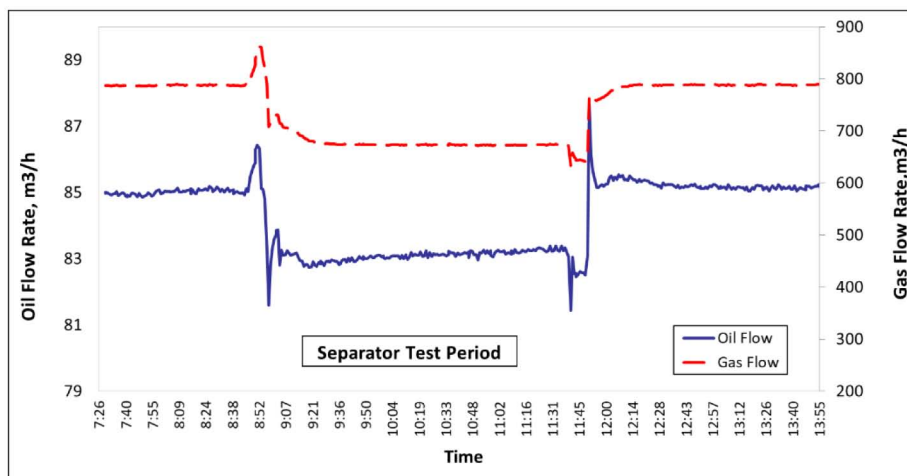


Figure 9—Oil and Gas Flow Rates during Tune Up Test (28/05/2018 MPFM P25).

Figure 10 shows the oil and gas flow rates during the Validation test performed on 30/05/2018 for validation of calibration at the same MPFM.

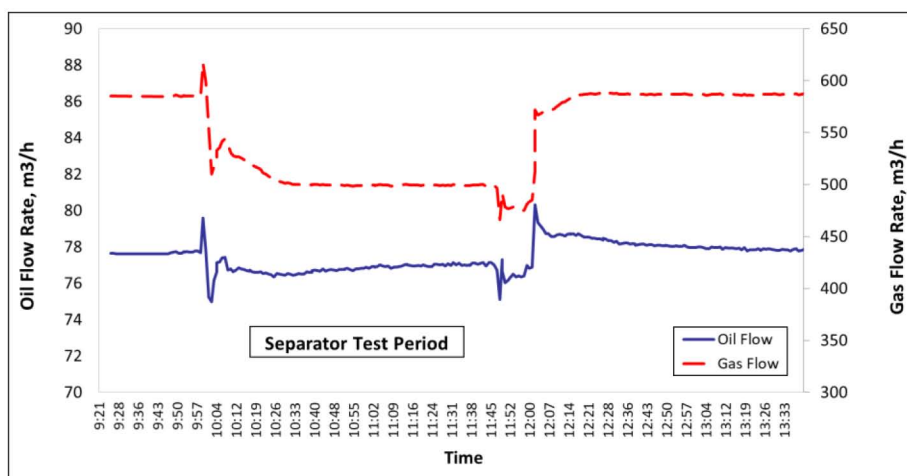


Figure 10—Oil and Gas Flow Rates during the Validation Test (30/05/2018 MPFM P25).

After each separator test, an ACT (Accuracy Certificate of Test) is signed by customer and operator which details the match between the Test Separator and MPFM as shown in Table 1 & 2.

Table 1—MPFM accuracy as per Tune Up Test for MPFM P25 28/05/2018

Equipment	Oil flow rate at actual condition, m3/hr	Oil flow rate at standard condition, Sm3/hr	Gas flow rate at standard condition, Sm3/hr
ESMER MPFM Measurements	83.1	73.5	16350.7
HBP Separator Measurements	77.6	67.1	14497.3
Comparison, %	7.13	9.58	12.78

Table 2—MPFM accuracy as per Validation Test for MPFM P25 30/05/2018

Equipment	Oil flow rate at actual condition, m3/hr	Oil flow rate at standard condition, Sm3/hr	Gas flow rate at standard condition, Sm3/hr
ESMER MPFM Measurements	76.8	68.0	15375.2
HBP Separator Measurements	77.5	67.3	14577.8
Comparison, %	-0.84	0.99	5.47

The field tune up procedure can be repeated at intervals determined by the operator as flow conditions change. An electronic database is kept for the history of Tune Up and Validation Tests including the inputs and outputs of the tests. Because P25 is a newly installed MPFM and hasn't got a long history another MPFM P14 is given as an example. Figures 11 and 12 give the oil and gas rate well test performance for MPFM P14 since inception on 20/03/2017.

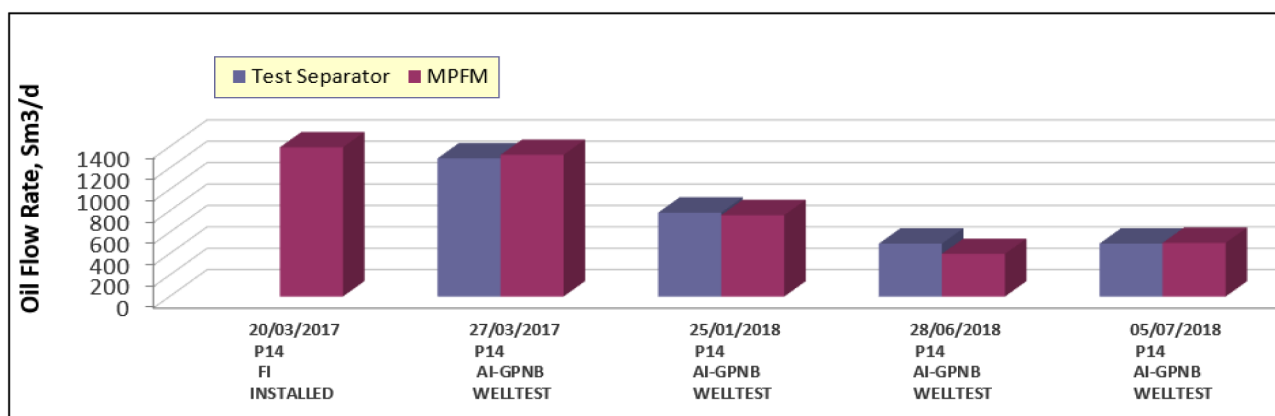


Figure 11—Tune Up / Validation History-Oil Flow Rate for MPFM P14.

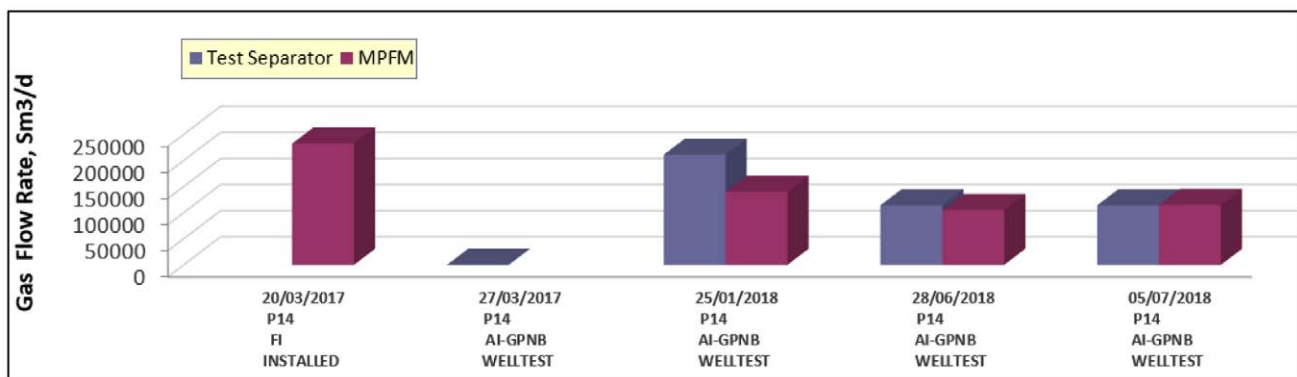


Figure 12—Tune Up / Validation History-Gas Flow Rate for MPFM P14.

Validation by Mass Balance - MPFMs vs Central Processing Facility

Field block diagram PID is shown in Figure 13. The field comprises a total of seventeen 6" well head MPFMs (one at each well head) and three 14" production line MPFMs (one at each trunk line to CPF).

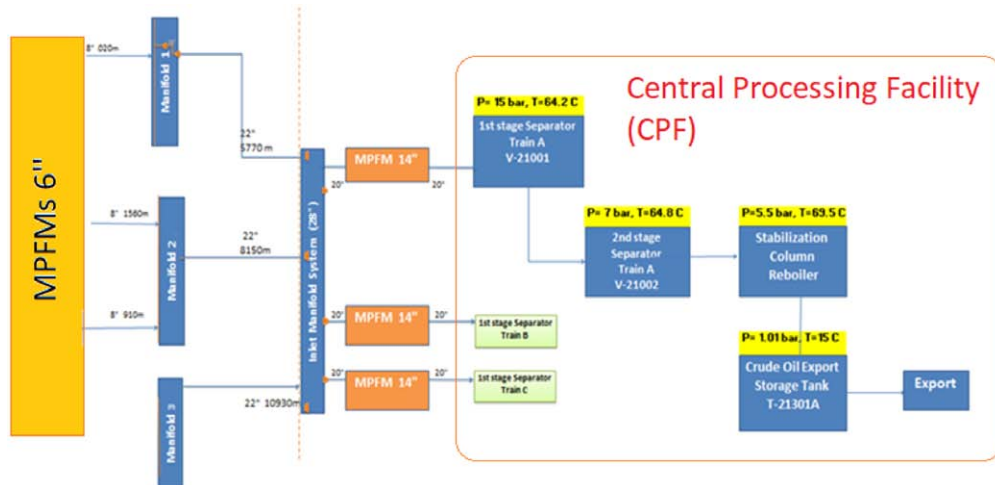


Figure 13—Illustration of CPF Inlet Area.

Total production measured by well head MPFMs and production line MPFMs are compared against each other and with the CPF (Central Process Facility) test separator on a daily basis. Figure 14 gives an example of the cumulative daily average of wellhead MPFMs vs Production Separator at the Central Processing Facility (CPF) for one month June-July 2017. The target accuracy is for the mass balance to agree within 5 % for the oil phase and within 10% for the gas phase. In general, we have noted a trend that the overprediction of one phase is accompanied by an underprediction of the other.

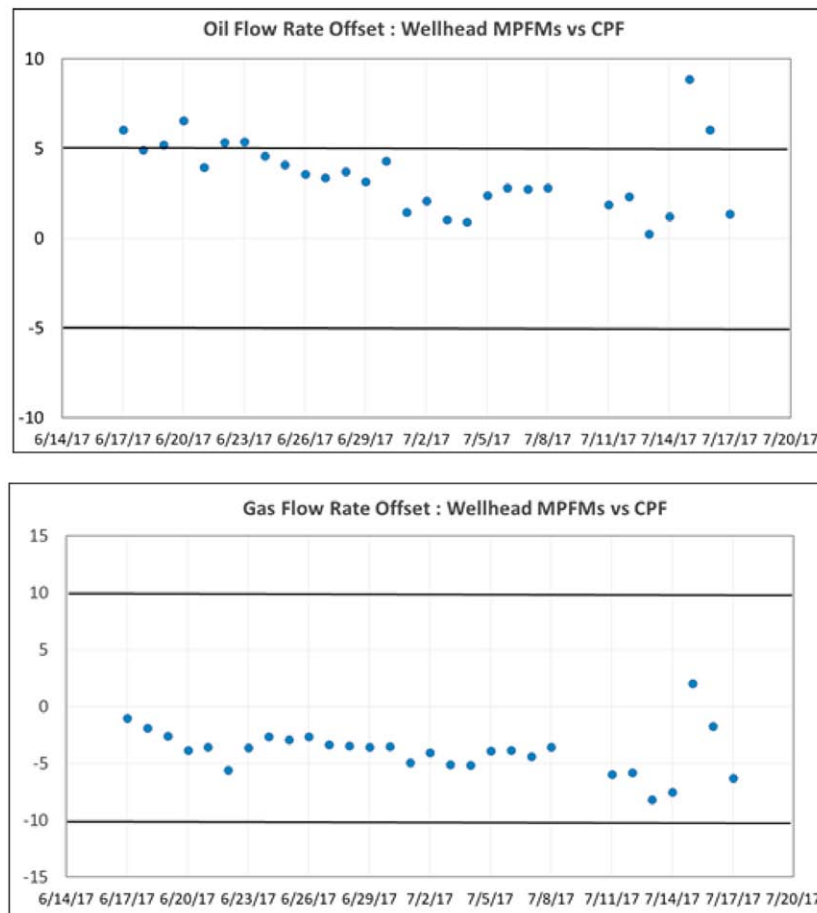


Figure 14—Daily production measured by Well Head MPFMs (6" MPFMs) versus CPF Separator (Example 17.06.2017-17.07.2017).

A cross check is also regularly carried out between the well head and production line MPFMs. Figure 15 shows an example of such check during the course of one month in June-July 2017.

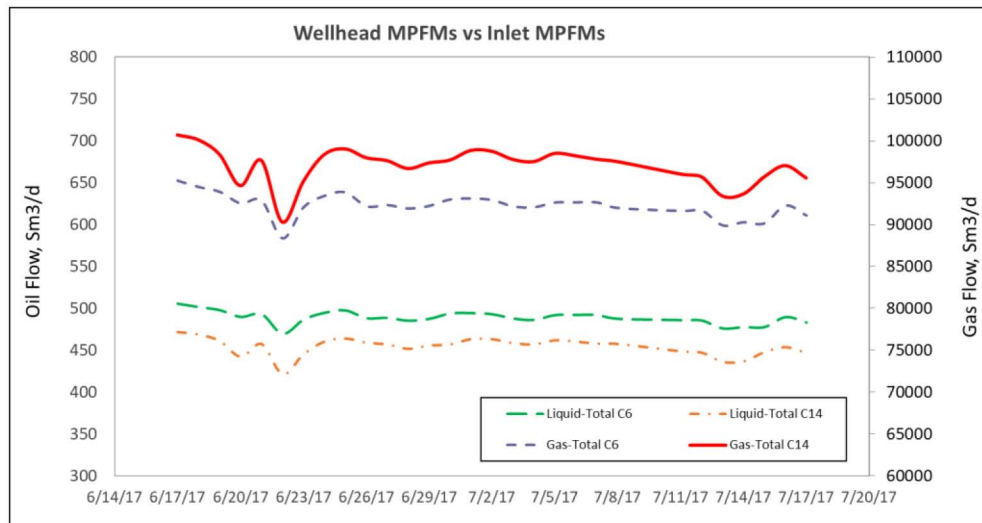


Figure 15—Daily production measured by Well Head MPFMs (6" MPFMs) versus Production MPFMs (14") (Example 17.06.2017-17.07.2017).

Neural Net Applications in Multiphase Flow – Field as Laboratory

We have used the field data to test some ideas for the application of neural nets in multiphase flow metering. For the avoidance of doubt, we should mention that R&D studies and results presented in this section do not impinge on the daily functioning and performance of the MPFMs.

Oil, gas and water flowing together in a pipeline gives rise to characteristic patterns which can be readily identified by neural nets. Such patterns can be related directly to flow rates (eg neural net as a flow meter) as well as other specific "states of the flow line" (eg malfunction detection, leak detection, etc). Inputs to the neural net are the "salient" stochastic features selectively extracted from a plurality of signals (eg P, T, DP, RDP, etc) [7,8]. In the case of supervised nets, outputs can be "tags" (eg malfunction of a certain type) or flow rates (eg measured by the test separator). In the case of unsupervised neural nets signals can self classify (no targets) to identify "rogue" vs "normal" conditions (example).

Training the Neural Net in the Flow Loop (Factory Neural Net)

As an example of the power of the supervised neural nets (as a multiphase flow meter) we can refer the reader to the results of the NEL flow loop test are shown in Figure 16 below giving a comparison of MPFM measurements against reference flow rates. The neural net trained with flow loop references was demonstrated to show an offset within $\pm 5\%$ in a blind test [5].

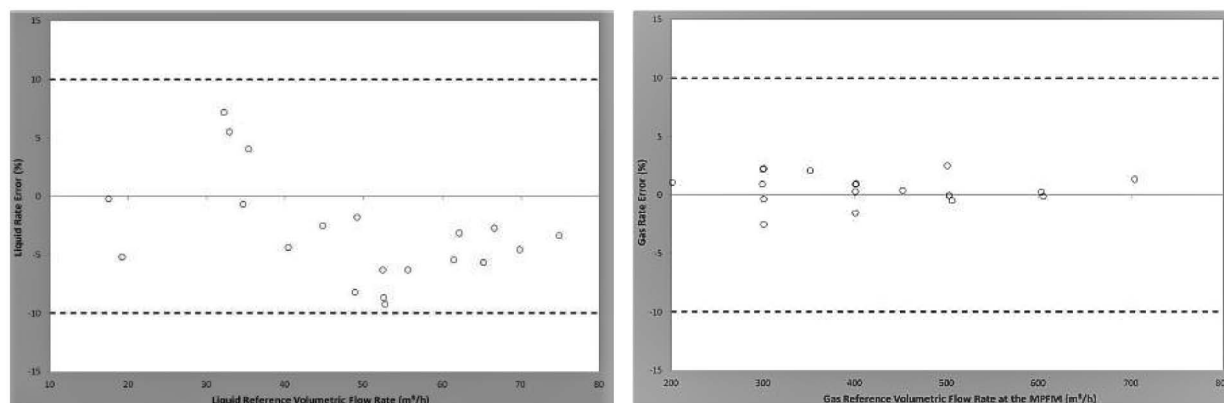


Figure 16—Flow Loop test results for liquid and gas rate.

Transfer Learning

Transfer learning is a machine learning method which aims to transfer the knowledge to a target task when it has fewer high quality data. In this method, a model developed for one case is reused as the starting point to create a model for another case [9]. We have evaluated the possibility of adapting the factory neural net (high quality data) to field conditions (lower quality data) by adding some measurements extracted from the field (MPFM logs of signals as inputs and measurements as reference outputs) into the original flow loop data set.

An example exercise was carried out for three MPFMs with data taken from the flow computer log on 30/06/17 and 01/07/17. Factory neural net (comprising 65 points) was retrained with the addition of 3 points (average of one hour selected at random from the 24 hour record on 30th June) for each one of the three selected MPFMs. The neural net was tested with input signals from 01/07/2017 and the predictions (neural net outputs) were compared with original measurements (made by the MPFM with its usual hydro-thermodynamic model) on a minute by minute basis.

Table 3 shows the Offset (average for the day) between prediction and measurement for the Factory Net and the Adapted Net. An improvement is already evident with the addition of just three transfer learning points to the factory data set. We've observed diminishing returns when further field points were added. It is seen that the neural net is more successful with the high producers where the flow rates are closer to those in the flow loop.

Table 3—Neural Net as a Flow Meter – Factory Net and Adapted Net Results.

Offset % (Average for the Day)	BD2	P09	P07
	01/07/2017	01/07/2017	01/07/2017
	High producer	High producer	Low producer
Oil Flow - Factory Net	-5.5	10.5	19.9
Oil Flow – After Transfer Learning	-2.25	-1.67	-10.33
Gas Flow - Factory Net	-10.4	-19.2	-16.9
Gas Flow – After Transfer Learning	1.35	-0.73	2.82

Malfunction Detection

This study was stimulated following an alert communicated by the operator on 14-08-2016 that liquid and gas flow rates measured by the MPFM at BD5 was increasing while the flowing well head pressure was declining gradually (Fig. 17).

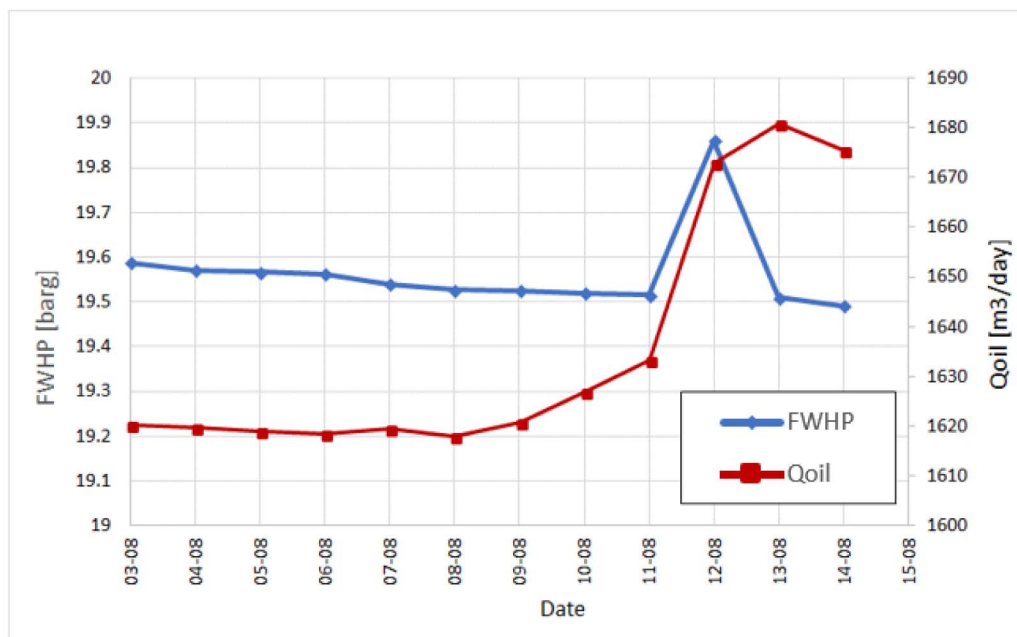


Figure 17—Unusual behaviour of MPFM in August 2017.

Later investigations (taking down the MPFM) revealed a partial blockage over the cone. This would have resulted in an increase in the total pressure drop over the differential device and an overprediction of the flow rate. Such cause and effect can be identified after the event from a cursory inspection of the time series but not known at the time (Fig 17).

We have used the incidence as a test case for automatic malfunction detection by neural nets. The question we are asking is *whether the neural net trained online can provide early warning of a malfunction*.

A data set was compiled over healthy and unhealthy periods from BD5 MPFM log, comprising 250 unhealthy points from 11:36 to 15:17 on 14-08-2016 and 150 healthy points 00:01 to 02:23 on 14-07-2016 (contiguous time series). Out of the total of 400 points in the data set, 211 were selected at random for training (remaining 189 earmarked for testing).

The input parameters to the neural net included the "mean and standard deviation feature" derived from all transmitter signals. We should note that mean DP was excluded since any normal flow rate changes would also be directly reflected on DP.

The neural net targets were tagged with 0 for healthy and 1 for the unhealthy points. We've named this the Malfunction Index (a continuous index of shades of gray in between 0 and 1). The neural net was tested with the 189 points (left out of the original set of 400). All points were correctly identified by the neural net as belonging to the healthy / unhealthy data sets (output was either zero or one). Next, the same neural net was applied to the entire month prior to the malfunction from 14-07-2016 to 14-08-2016. In this case the output was a number between zero and one.

Figure 18 shows that the Malfunction Index is shifting from 0 (healthy) to 1 (unhealthy) over the said period. This is in line with the expectation of cone blockage as a gradual process. The neural net offers the potential for providing early warning before blockage as the shift from 0 to 1 kicks in prior to "alarm" point. Early results reported here are encouraging but further testing is required before the scheme can be implemented on the live system.

