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Advanced DP Meter Diagnostics – Developing Dynamic Pressure Field Monitoring (& Other Developments)

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1 INTRODUCTION

Differential Pressure (DP) meters have a full diagnostic suite. These diagnostics appeared suddenly and unexpectedly. Due to the DP meter's simplicity there was a long standing axiom that DP meters could have no diagnostics. For more than a century DP meter operators were unaware of the information contained in a DP meter's pressure field. Operators of DP meters traditionally knew of only a small proportion of the information available from each DP meter. However, DP meter technology has now evolved the ability to see and understand the pressure field. This crucial DP meter evolutionary step has diverted the DP meter from the slow road to obsolescence and placed it firmly back in the forefront of modern flow meter development.

In one short evolutionary step the development of pressure field monitoring diagnostics transformed the DP meter from a 'dumb' device into a 'smart' device. Pressure field monitoring gave DP meter technology the capability to make complex discriminations it was entirely incapable of making before. The scale of the expansion of DP meter diagnostic capability has swept away a long held axiom regarding DP meters being an evolutionary dead end. The suddenness of this change has inevitably meant that many are yet to fully grasp the new potential of the DP meter. The importance of this development means that many are yet to fully grasp the likely long term consequences of this change. The development of pressure field monitoring has produced a multiplicative effect. It has not only exposed the potential for DP meters to have a robust, comprehensive and easily understandable diagnostic system, but also for new DP meter capabilities to be developed.

DP meters that use these diagnostics are far more capable than those that don't. The diagnostics are powerful, comprehensive and are becoming established, but they are still developing on two fronts. First, the existing diagnostic concepts are now being applied to not just standard DP meters for serviceability checks, but specifically to expand the capabilities of DP meters in traditionally adverse flow condition applications. Secondly, the existing diagnostic suite is being developed. Whereas present techniques compare a 'static' instantaneous (or time averaged) pressure field picture to a fixed expected baseline, more advanced techniques are now being developed that also monitor the 'dynamic' pressure field fluctuations over time.

This paper covers:

- a review of the latest diagnostic suite (with some field trial results),
- a review of new DP meter applications and capabilities that are now being researched and developed based on these DP meter pressure field monitoring techniques,
- techniques specifically for monitoring known problems and trends,
- new dynamic response diagnostics.

2 DP METER DIAGNOSTICS

Swinton Technology partnered with DP Diagnostics to produce the generic DP meter diagnostic suite 'Prognosis' (see Steven [1, 2]). An overview of these patented 'pressure field monitoring' diagnostics is now given. For details the reader should refer to the descriptions given in by Steven [1, 2], Skelton et al [3] & Rabone et al [4].

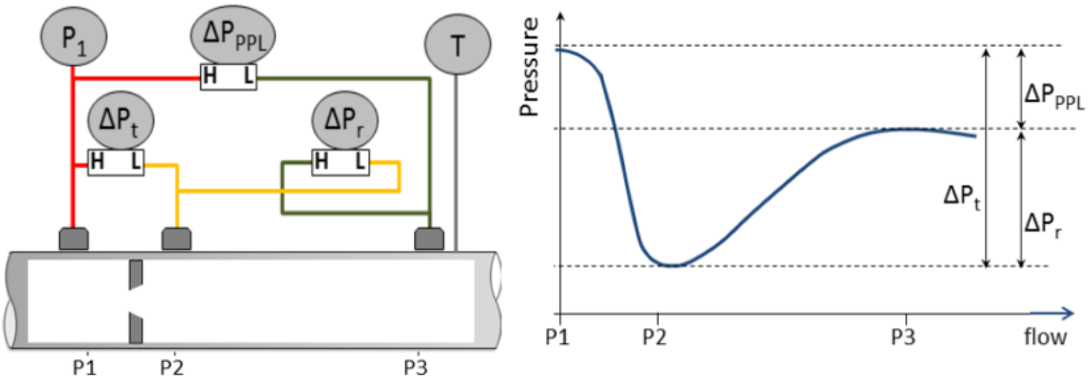

Fig 1. Orifice meter with instrumentation sketch and pressure field graph.

Figure 1 shows a sketch of a generic DP meter and its pressure field. The DP meter has a third pressure tap downstream of the two traditional pressure ports. This allows three DPs to be read, i.e. the traditional (ΔP_t), recovered (ΔP_r) and permanent pressure loss (ΔP_{PPL}) DPs. These DPs are relate by equation 1. The percentage difference between the inferred traditional DP (i.e. the sum of the recovered & PPL DPs) and the read DP is δ%, while the maximum allowed difference is θ%.

DP Summation:	$\Delta P_t = \Delta P_r + \Delta P_{PPL}$,	uncertainty ± $\theta\%$	--- (1)
Traditional flow calculation:	$\dot{m}_{trad} = f_t(\Delta P_t)$,	uncertainty ± x%	--- (2)
Expansion flow calculation:	$\dot{m}_{\exp} = f_r(\Delta P_r)$,	uncertainty ± y%	--- (3)
PPL flow calculation:	$\dot{m}_{PPL} = f_{PPL}(\Delta P_{PPL})$,	uncertainty ± z%	--- (4)

Each DP can be used to meter the flow rate, as shown in equations 2, 3 & 4. Here $\dot{m}_{trad}$, $\dot{m}_{\exp}$ & $\dot{m}_{PPL}$ are the mass flow rate predictions of the traditional, expansion & PPL flow rate calculations. Symbols f_t, f_r & f_{PPL} represent the traditional, expansion & PPL flow rate calculations respectively, and, $x\%$, $y\%$ & $z\%$ represent the uncertainties of each of these flow rate predictions respectively. Inter-comparison of these flow rate predictions produces three diagnostic checks. The percentage difference of the PPL to traditional flow rate calculations is denoted as $\psi\%$. The allowable difference is the root mean square of the PPL & traditional meter uncertainties, $\phi\%$. The percentage difference of the expansion to traditional flow rate calculations is denoted as $\lambda\%$. The allowable difference is the root mean square of the expansion & traditional meter uncertainties, $\xi\%$. The percentage difference of the expansion to PPL flow rate calculations is denoted as $\chi\%$. The allowable difference is the root mean square of the expansion & PPL meter uncertainties, $\nu\%$.

Reading these three DPs produces three DP ratios, the 'PLR' (i.e. the PPL to traditional DP ratio), the PRR (i.e. the recovered to traditional DP ratio), the RPR (i.e. the recovered to PPL DP ratio). DP meters have predictable DP ratios. Therefore, comparison of each read to expected DP ratio produces three diagnostic checks. The percentage difference of the read to expected PLR is denoted as $\alpha\%$. The allowable difference is the expected PLR uncertainty, $a\%$. The percentage difference of the read to expected PRR is denoted as $\gamma\%$. The allowable difference is the expected RPR uncertainty, $b\%$. The percentage difference of the read to expected RPR is denoted as $\eta\%$. The allowable difference is the expected RPR uncertainty, $c\%$.

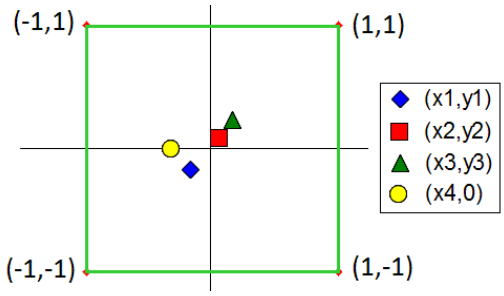

Fig 2. Normalized Diagnostic Box (NDB) with diagnostic results

These seven diagnostic results can be shown on the operator interface as plots on a graph. That is, we can plot (Figure 2) the following four co-ordinates to represent the seven diagnostic checks: $(\psi\%/\phi\%, \alpha\%/a\%)$, $(\lambda\%/\xi\%, \gamma\%/b\%)$, $(\chi\%/\nu\%, \eta\%/c\%)$ & $(\delta\%/\theta\%, 0)$. For simplicity we can refer to these points as (x_1,y_1), (x_2,y_2), (x_3,y_3) & $(x_4,0)$.

The act of dividing the seven raw diagnostic outputs by their respective uncertainties is called 'normalisation'. A Normalised Diagnostics Box (or 'NDB') of corner coordinates (1,1), (1,-1), (-1,-1) & (-1,1) can be plotted on the same graph (see Figure 2). This is the standard user interface with the diagnostic system 'Prognosis'. All four diagnostic points inside the NDB indicate a serviceable DP meter.

In this paper it will be shown that for the special case of monitoring the severity of a **known** problem, such as levels of contamination of a meter run or the liquid loading of a wet gas flow, the reference with which to compare the found performance is arbitrary. When monitoring changes in the severity of a problem, it is just as valid to use the meter performance at a known finite level of the problem as the reference as it is to use the correctly operating meter performance. In this scenario there is no need to normalise diagnostic data, as the uncertainty of the baseline diagnostic parameters is not relevant to the task at hand. How the diagnostic points move relative to changes in the known problem is what is important, not changes relative to the correctly operating meter baseline. Hence, for trend monitoring, there is no need to normalise the data. Without normalised data the NDB must be removed as it is then meaningless. In this case we can monitor 'raw', i.e. un-normalised, diagnostic points by plotting $(\psi\%, \alpha\%)$, $(\lambda\%, \gamma\%)$, $(\chi\%, \eta\%)$ & $(\delta\%, 0)$. In this case the correctly operating DP meter performance or the last read result are obvious candidates for the arbitrary diagnostic reference.

3 REVIEW OF SOME DP METER R&D PROJECTS BASED ON PRESSURE FIELD MONITORING

The advent of DP meter pressure field monitoring diagnostics has allowed DP meters to be considered for applications where they (and all) meters may traditionally struggle. Research & development projects have grown from these DP meter diagnostics. A summary of some of these projects are given in Section 3.

3.1 Contamination Monitoring (by CEESI, DP Diagnostics, & Various Operators)

Industrial gas flows can contaminate a meter run over time thus adversely affecting the flow meter. In 2009 Steven [2] showed with laboratory test results the effect on an orifice meter if the plate became contaminated. Contamination induced a negative flow rate prediction and the diagnostic system indicated that the meter output was in error. However, in real applications contamination coats the meter and meter run.

Over the last few years CEESI has received multiple enquires regarding contaminated meter testing. In some of the projects the DP meter diagnostic system 'Prognosis' was included on orifice meters. Following an early client test where a heavy grease and soda bicarbonate mixture was used as a contaminant, CEESI has subsequently used this mixture as a default contaminate. Figure 3 shows the inside of a clean 4", sch 80, 0.50β senior fitting orifice meter. Figures 4 & 5 show two different levels of contamination applied 15D upstream and 8D downstream of a straight orifice meter run. Prognosis was applied using the ISO 5167 Part 2 derived baseline parameters.

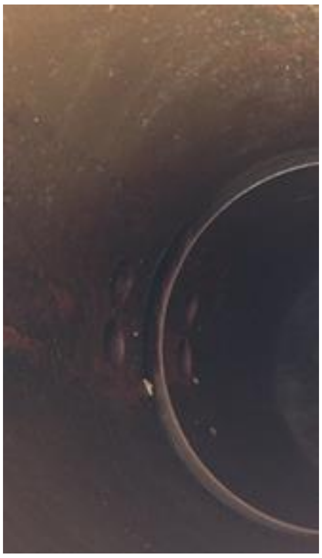

Fig 3. Clean Orifice Meter

Fig 4. Light Contamination

Fig 5. Moderate Contamination

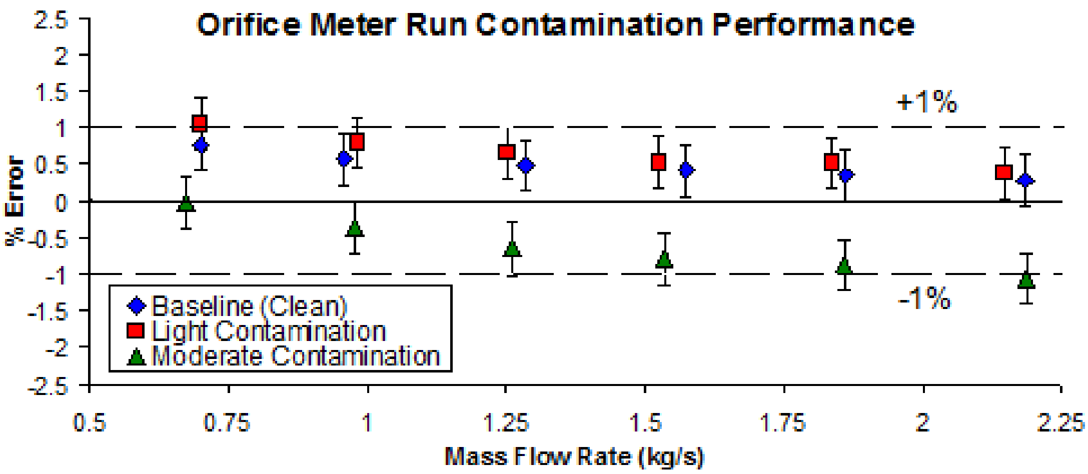

Fig 6. Orifice Meter Performance with varying Contamination Levels.

Figure 6 shows the response of the orifice meter to different levels of contamination. These results were read from air flow at 30 Bar and 25^{0}C. The orifice meter's output is compared to the gas turbine meter reference flow rate of 0.35% uncertainty (see error bars on Figure 6 data). It is immediately notable that the contamination has a surprisingly small effect on the meter's performance. If we consider the orifice meter's overall flow rate prediction uncertainty to be 0.7% (i.e. API 14.3) we see that the clean orifice meter agrees with that specification. The light contamination had virtually no adverse effect. The heavier contamination had a noticeable but small effect, causing the meter to read a slightly lower flow rate, which only approached -1% bias at higher flow rates.

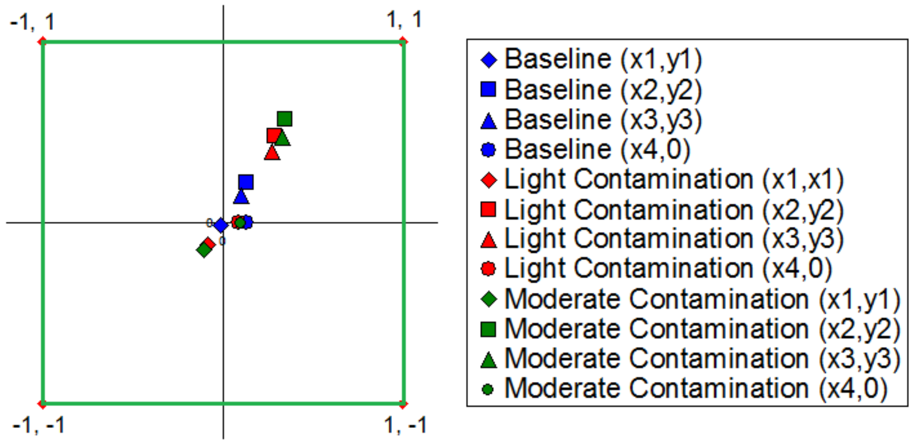

Fig 7. Sample Prognosis Results, 3 Contamination Levels Superimposed on Graph.

Figure 7 shows three sample Prognosis results; each are the maximum flow rates tested for the clean, light and heavier contaminations. The default Prognosis sensitivity settings of x=0.5%, y=2%, z=2%, a=4%, b=2.5%, c=3% & θ =1% were used. None of the three examples show a diagnostic warning. However, if we consider Figure 6 this is not particularly surprising, as the contamination is not causing much of a flow rate prediction bias. Not one of the test results could be confirmed to be causing the orifice meter to be in error by greater than ±1%. Prognosis has been shown to be capable of seeing many flow rate prediction errors to within 1% of the actual flow rate, and most flow rate prediction errors to within 1% of the stated meter uncertainty. Therefore, here Prognosis is indicating no meter malfunction as the orifice meter is still giving the gas flow rate to <1%. <u>Prognosis looks for ***actual*** flow rate prediction errors, which is a subtle but important difference to looking for non-compliance with standard documents!</u> An ISO non-compliant orifice meter can often still predict the correct flow rate (to within the meter's uncertainty).

Figure 7 does show that the increasing contamination has an affect on the diagnostics. As the contamination increases the points (x_1,y_1), (x_2,y_2) & (x_3,y_3) diverge from the origin. The point $(x_4,0)$ remains close to the origin as it should, as the DPs are being correctly read. If it is known that the meter will suffer from a particular problem, Prognosis can be used to monitor that particular problem. If contamination is a constant concern Prognosis can monitor changing levels of contamination. If the system is to be used in this way, the operator can set Prognosis to show $(\psi\%,\alpha\%)$, $(\lambda\%,\gamma\%)$, $(\chi\%,\eta\%)$ & $(\delta\%,0)$. In practical terms this means setting the system sensitivity to x=1/√2%, y=1/√2%, z=1/√2%, a=1%, b=1%, c=1% & θ =1%. In this scenario the NDB has no meaning and can be ignored. Fig 7's results are re-plotted as Fig 7a. When monitoring specific issues, un-normalised data gives the most sensitive diagnostics.

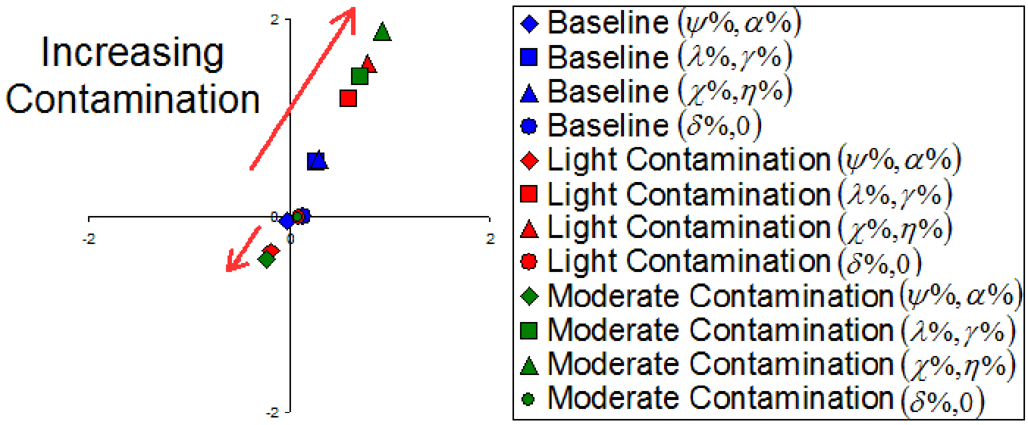

Fig 7a. Sample Un-Normalised Results, 3 Contamination Levels on Graph

This Operator / CEESI project to apply Prognosis to specifically monitor contamination levels is one example of how the advent of pressure field monitoring has not just created DP meter diagnostics but potentially expanding DP meter capabilities.

3.2 Erosion Monitoring (by RPSEA, LettonHall Group, TUVNEL & DP Diagnostics)

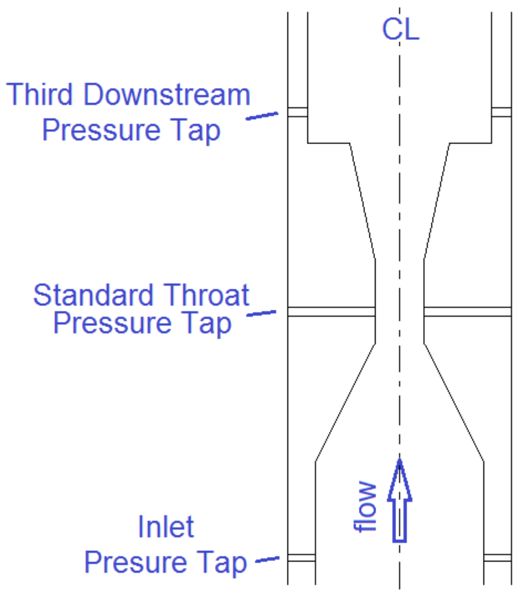

Fig 8. Modified Venturi Meter.

In 2011 the Letton-Hall Group and DP Diagnostics met at ConocoPhillips Houston office to discuss a RPSEA funded project. Letton-Hall were investigating for RPSEA ways of identifying erosion in multiphase meters. A third pressure tap downstream of the Venturi meter throat was being considered. It was postulated that if this third tap was in a section likely to have a slower erosion rate than the throat section then pressure field monitoring could identify erosion. That is, the DP Diagnostics pressure field monitoring techniques were being considered as a component of this complex research.

DP Diagnostics had previously shown that pressure field monitoring (i.e. 'Prognosis') was effective at monitoring DP meter erosion. For example, Steven [2] showed that Prognosis could see and trend orifice meter sharp edge erosion. However, multiphase flow meter erosion monitoring is a much more difficult task. There are multiple adverse effects on the Venturi meter, e.g. changing fluid properties & flow conditions, erosion and other unexpected issues. The patent holders DP Diagnostics gave RPSEA / Letton-Hall Group their blessing for the research.

Figure 8 shows a design subsequently developed by TUVNEL / Letton-Hall in this RPSEA desktop exercise. The scope of this project was limited, and further work would be required to develop this idea. This project is another example of how the advent of pressure field monitoring has not just created DP meter diagnostics but has potentially expanded DP meter capabilities.

3.3 Oil with Water Flow Metering (by CEESI & DP Diagnostics)

Oil with water flow metering typically uses a volume flow meter in series with a mixer / probe sample system. The flow meter gives the total flow rate, whilst the sample system gives the water cut. Combining these two values gives the oil and water flow rates. In order for this approach to give custody transfer flow rate prediction uncertainties, both the total flow rate and water cut predictions must have low uncertainties. It is therefore very desirable in custody transfer applications for the flow meter to have comprehensive diagnostics.

Of the three commonly used flow meters for this application, all have their flow rate prediction uncertainty and diagnostic capabilities adversely affected by the oil & water mix. The turbine meter has no diagnostics and the total flow rate prediction uncertainty expands considerably as the flow rate reduces and the oil & water separates (see Cousins et al [5]). The ultrasonic meter (USM) total flow rate prediction uncertainty is significantly higher at approximately 3% for oil with water flows compared to the homogenous oil flow uncertainty of < 0.2% (see Brown et al [6]). There is little in the literature with regard to a modern ultrasonic meter's diagnostic suite when the meter is used with oil with water flows. It is generally understood that the ultrasonic meter diagnostic suite would be significantly affected by the presence of water with the oil. The Coriolis meter total flow rate prediction uncertainty for oil with water flows is relatively good at approximately 0.5% (see Kegel et al [7]) but there is little in the literature regarding applying the Coriolis based diagnostics to the specific case of oil with water flows. Furthermore, Kegel [7] showed that water cut measurement via a Coriolis meter produced uncertainties well in excess of what would be acceptable for custody transfer metering. Hence, industry for the moment requires a sample system regardless of what flow meter is used.

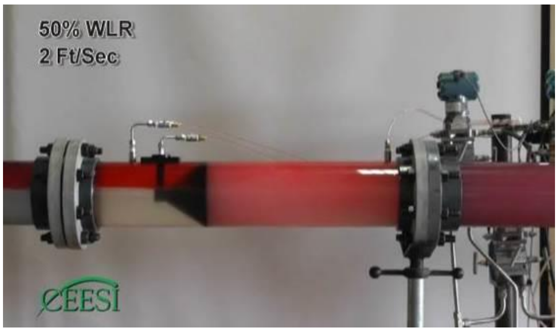

Fig 9. Cone meter, 0.6 m/s, ω_m 0.5.

Fig 10. Cone meter 1.6 m/s, ω_m 0.2.

CEESI and DP Diagnostics tested a clear body 6", 0.483β cone DP meter in horizontal oil with water flows (see Cousins et al [5]). Figures 9 & 10 show oil (dyed red) and water flowing through a cone meter. Note that the velocities are the average flow velocity and 'ω_m' is the ratio of water to total liquid mass flow. Figures 11 & 12 show the oil only and water only calibration results. The type of homogenous fluid had no effect on the DP meter performance. Figure 13 shows Prognosis calibration results. The meter was fully diagnostic ready when tested with oil and water mixtures.

Cousins et al [5] discussed in detail the DP meter's response to use in oil with water flow metering applications. The DP meter had as good a performance in this application as turbine and ultrasonic meters. The Coriolis meter had the best flow rate prediction, but as with the turbine and ultrasonic meters the diagnostic capability was adversely affected by the oil and water mixture. Only the DP meter had a fully serviceable diagnostic system when used with oil and water applications.

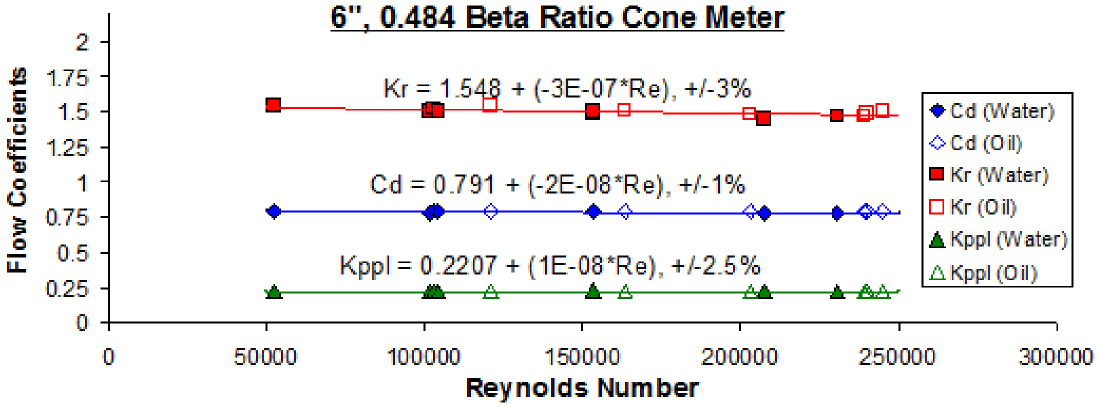

Fig 11. 6", 0.483β Cone Meter Flow Coefficients in Homogenous Liquid Flow.

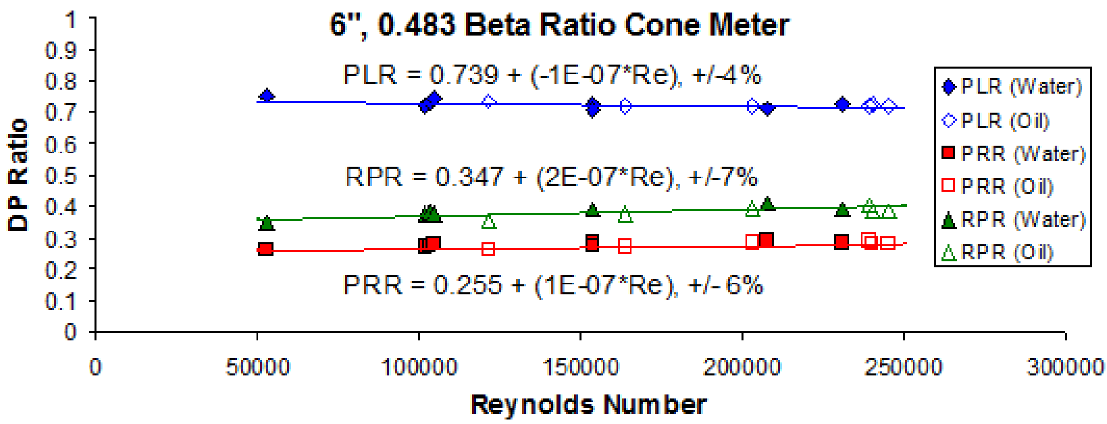

Fig 12. 6", 0.483β Cone Meter DP Ratios in Homogenous Liquid Flow.

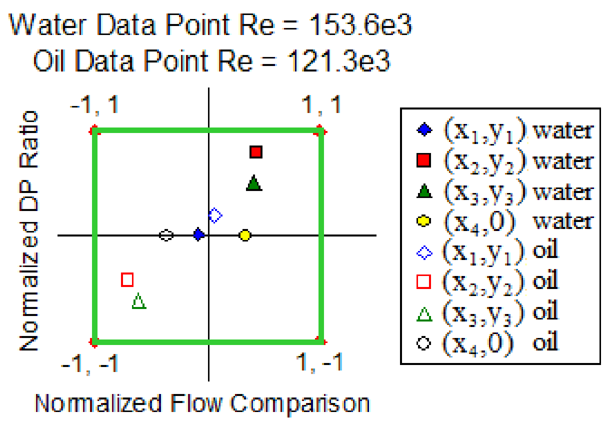

Fig 13. Examples of Baseline Diagnostic Results.

Figure 14 shows sample diagnostic results for the cone meter when it was used with various flow rates and water liquid ratios (i.e. 'WLR'). The diagnostics are immune to the fact that there is oil and water present. The DP meter has a diagnostics suite that is wholly unaffected by the oil and water mix. It is therefore fully available to clearly indicate the serviceability of the meter in an oil with water flow application. For example, Figure 15 shows a Prognosis results for the case of a correct and then incorrect discharge coefficient being entered. The flow is an oil with water flow (of WLR 23%). The actual input is C_d=0.791+ (-2e-**8***Re) which as way of example was entered as C_d=0.791+ (-2e-7*Re) inducing a flow rate prediction bias of -4.6%. Figure 15 shows Prognosis indicating a metering problem. Figure 16 shows Prognosis results for the case where the traditional DP reading is read correctly and then incorrectly. The flow is an oil with water flow (of WLR 6%). The actual traditional DP is 105.8"WC (26.3 kPa), but let us consider the case if the DP transmitter was, say, saturated at 100"WC (24.86 kPa). The induced flow rate prediction error would be approximately -2.8%. Figure 16 shows Prognosis indicating a metering problem.

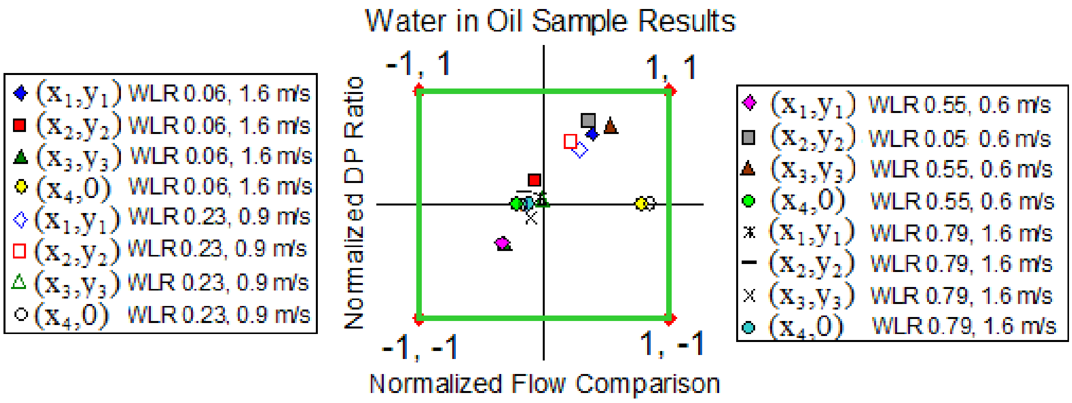

Fig 14. Sample Data from a 6", 0.483β Cone Meter Tested with Oil with Water Flows.

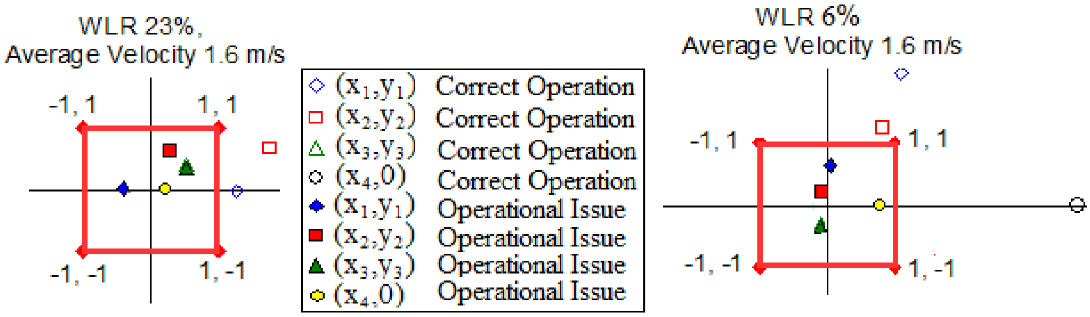

Fig 15. Incorrect C_d.

Fig 16. Incorrect DP_t Read.

This project is another example of how the advent of pressure field monitoring has not just created DP meter diagnostics but has potentially expanded DP meter capabilities.

3.4 Heavy Oil Flow Metering (by TUVNEL, DP Diagnostics & Swinton Technology)

With much of the world's remaining hydrocarbon deposits held in heavy (highly viscous) oil, metering of heavy oil flows is becoming ever more important. However, it is a challenge to meter heavy oil flow. The high viscosity means that heavy oil production flows tend to have very low Reynolds numbers. Most flow meters have non-linear flow coefficients in low Reynolds number ranges. Hence, it is critical to know the viscosity and therefore the Reynolds number to low uncertainty, so that the flow coefficient and the flow rate can be known to low uncertainty. However, it is a challenging problem to know the viscosity of a heavy oil production flow, as viscosity changes significantly with temperature and composition. It was to this problem that the DP Diagnostics concept of DP meter pressure field monitoring was applied by TUVNEL & DP Diagnostics.

In 2012 TUVNEL undertook a heavy oil research project under contract to the UK Government's Department for Innovation, Universities and Skills as part of the

National Measurement System's Engineering and Flow Programme. An 8", 0.6β Venturi meter with a downstream pressure tap (see Figure 17) was tested with Aztec fluid (viscosity 0.87 Pa.s). Figures 18 & 19 show the pressure field analysis, i.e. the Prognosis calibration results. As with all flow meter designs at this low Reynolds number range the Venturi meter is highly influenced by Reynolds number. All six diagnostic parameters are fitted to Reynolds number. It is this phenomena that allows Prognosis to be very useful with heavy oil flow. If a given meter is calibrated in heavy oil to characterize the Prognosis parameters then the Venturi meter with Prognosis can be used as a combined viscosimeter and a flow meter.

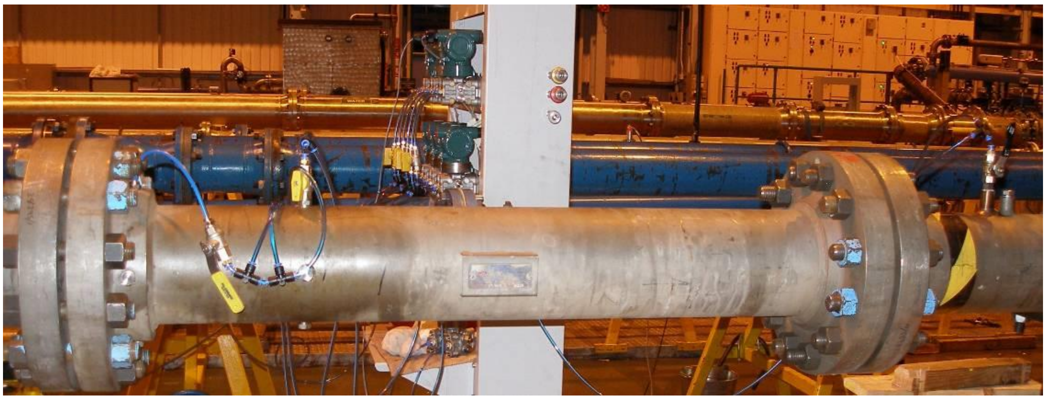

Fig 17. Venturi Meter with Downstream Pressure Tap Installed at TUVNEL Heavy Oil Flow Facility (Flow Left to Right).

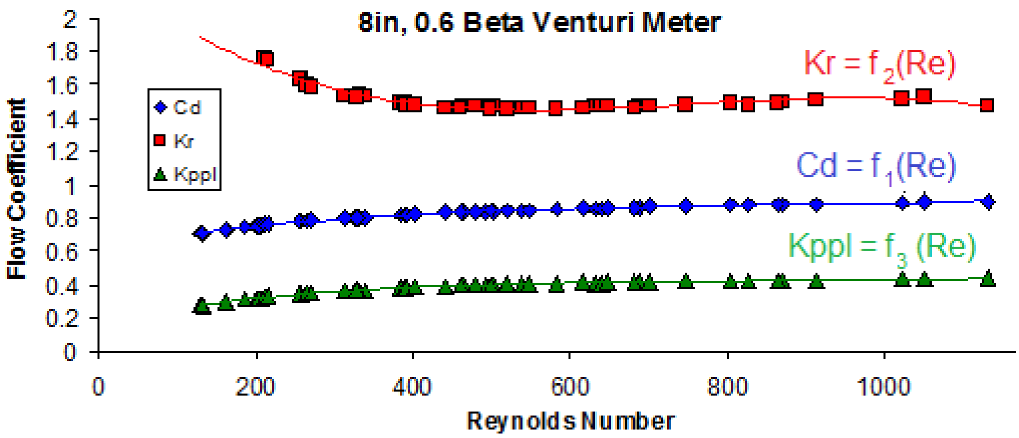

Fig 18. 8", 0.6β Venturi Meter Flow Coefficients vs. Reynolds Number.

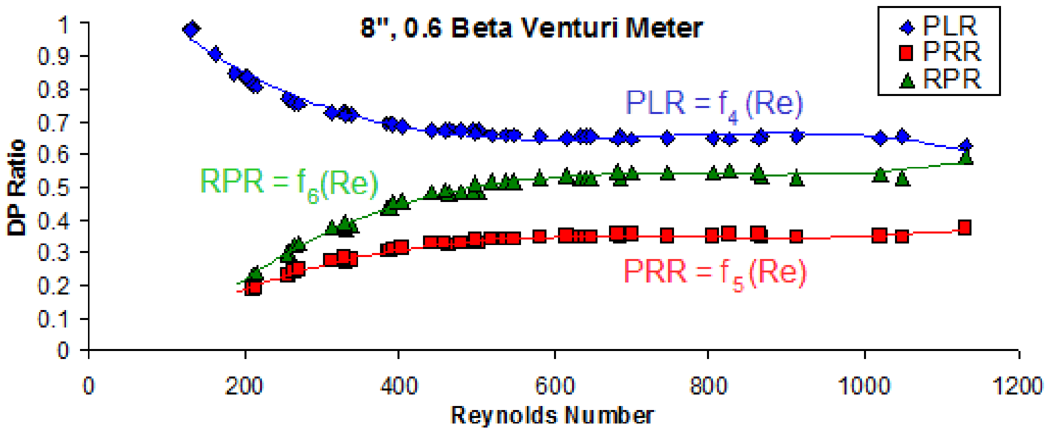

Fig 19. 8", 0.6β Venturi Meter DP Ratios vs. Reynolds Number.

Figure 20 shows all TUVNEL heavy oil data applied to Prognosis for the case of known viscosities and the flow coefficients and DP ratios being fitted to the Reynolds number. In practice, while the operator knows the calibrated discharge coefficient and other diagnostic parameters relationships, the operator often struggles to know the actual fluid viscosity as the temperature and composition vary over time. It is here that Prognosis can become a significant benefit. Prognosis can tell the operator the viscosity thereby allowing the Reynolds number, discharge coefficient and flow rate to be derived. The following example shows this process.

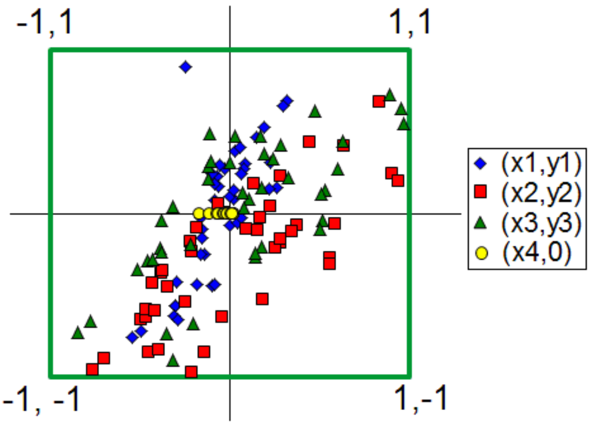

Fig 20. All TUVNEL 8", 0.6β Venturi Meter Prognosis Results.

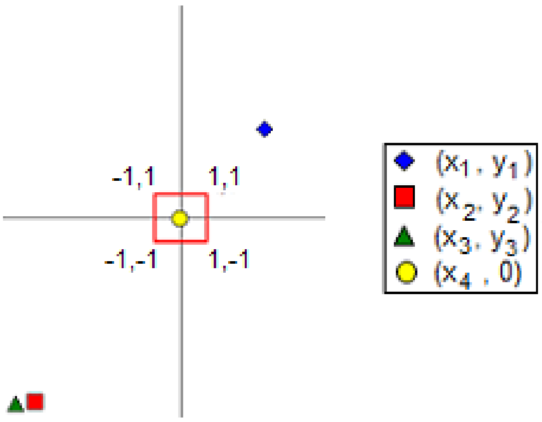

Fig 21. 8", 0.6β Venturi Meter 1st Viscosity Guess 0.5 Pa.

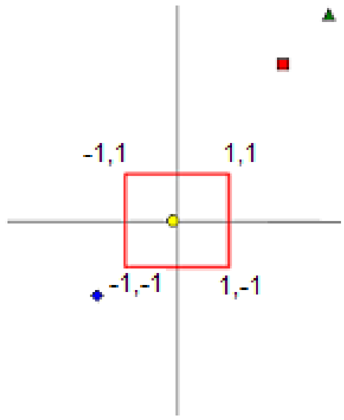

Fig 22. 8", 0.6β Venturi Meter 2nd Viscosity Guess 0.5 Pa.

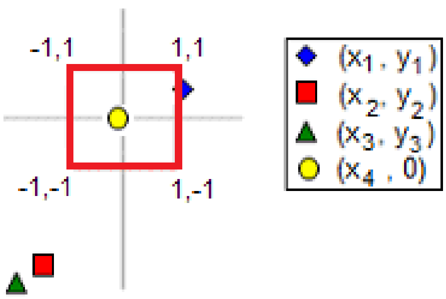

Fig 23. 8", 0.6β Venturi Meter 3rd Viscosity Guess 0.75 Pa.

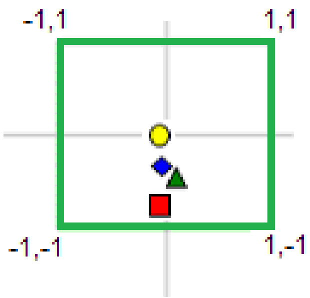

Fig 24. 8", 0.6β Venturi Meter 4th Viscosity Guess 0.85 Pa.

Consider a data point with a mass flow of 35.5 kg/s, a Reynolds number of 255, and a fluid viscosity (μ) of 0.87 Pa.s. For a known viscosity this flow point is included in Figure 20. However, in the field the operator may not know the viscosity. Say a viscosity of 0.5 Pa. is assumed, then the flow rate prediction is 38.34 kg/s, which is an error of +7.9%. Figure 21 shows the Prognosis response. Accepting that the problem is an unknown viscosity then Prognosis is saying that viscosity is in error. The operator must iterate to find the correct viscosity.

Try the higher viscosity of 1 Pa.s. Figure 22 shows the Prognosis result. A meter error is still shown and the pattern has inverted. This indicates that the viscosity value was increased too much. Trying the mid viscosity of 0.75 Pa.s gives Figure 23. A meter error is shown, but the points are getting closer to the NDB and the pattern has inverted back to indicating the viscosity input is now slightly too low. A further iteration to a viscosity of 0.85 Pa.s is shown in Figure 24. All points are now in the NDB. The estimated viscosity is 0.85 Pa.s, the associated Reynolds number is estimated at 262 and the flow rate is estimated at 35.46 kg/s, i.e. -0.23% difference from the reference meter's value. Prognosis has estimated the viscosity, thereby allowing the Reynolds number, discharge coefficient and flow rate to be predicted with no external viscosity measurement required.

Rabone et al [8] reports on this heavy (high viscosity) oil flow metering research. This project is another example of how DP meter pressure field monitoring has expanded DP meter capabilities.

3.5 Metering High CO_2 Content Natural Gas Flows (by CEESI & DP Diagnostics)

The natural gas production industry is encountering more high carbon dioxide (CO_2) content natural gas flows. Also, around the world carbon capture projects are becoming a higher priority. There are two potential issues when metering high CO_2 content gas flows. The first is that the gas exhibits some unusual properties that could potentially adversely affect gas meter performance. The second is that the gas / liquid phase boundary of CO_2 is in the ranges of thermodynamic conditions that can be encountered in natural gas production. High carbon dioxide content natural gas flows may produce some liquid drop out. In this section the response of an orifice meter and its diagnostic system to high CO_2 natural gas flows is discussed. The tests were carried out by CEESI with gaseous phase flow only. (The response of an orifice meter and its diagnostic system to two-phase / wet gas flow will be discussed in Section 3.5).

Carbon dioxide has fluid properties that produce challenges for different gas meter types. Apart from the potential phase change issue, an Ultrasonic meter may have trouble with 'wave energy absorption by molecular thermal relaxation'. That is, if the ultrasonic transducer frequencies coincide with the natural frequency for which CO_2 absorbs wave energy the signal may be lost. It is the unusually low value of CO_2's compressibility which has caused some concern regarding turbine and DP meters. Unusual compressibility effects could ***potentially*** cause different lift and drag forces on gas turbine blades, and biases on expansibility calculations on gas DP meters.

In 2013 CEESI carried out a series of high CO_2 content natural gas flow tests. The CEESI wet gas test facility was utilised. The thermodynamic conditions were set such that phase change would not be an issue. As the performance of all gas meters was questioned, one aspect of this test was to compare the performance of gas meters that operate by utilising different physical principles. Any adverse effects due to the presence of a high CO_2 concentration should induce different problems on these different meter designs. Two of the gas meters chosen were an 8" turbine meter (Fig 25) with 0.75% mass flow rate prediction uncertainty and, an 8", 0.564β orifice meter inclusive of pressure field monitoring (Fig 26) with 0.7% mass flow rate prediction uncertainty. Due to other client meters installed in the facility the orifice meter was installed > 200D downstream of the turbine meter.

The Daniel Gas Chromatograph was calibrated with the appropriate test gas. AGA8 & RefProp software independently calculated the gas density from the GC output and read pressure & temperature. These density predictions agreed to < 0.02%. Standard natural gas (18mW) viscosity and isentropic exponents were used. As the turbine meter was the wet gas facility's normal primary reference gas meter, it was chosen as the arbitrary primary reference gas meter against which to compare the orifice meter.

Fig 25. CEESI 8" Turbine Meter.

Fig 26. CEESI 8" 0.564β Orifice Meter

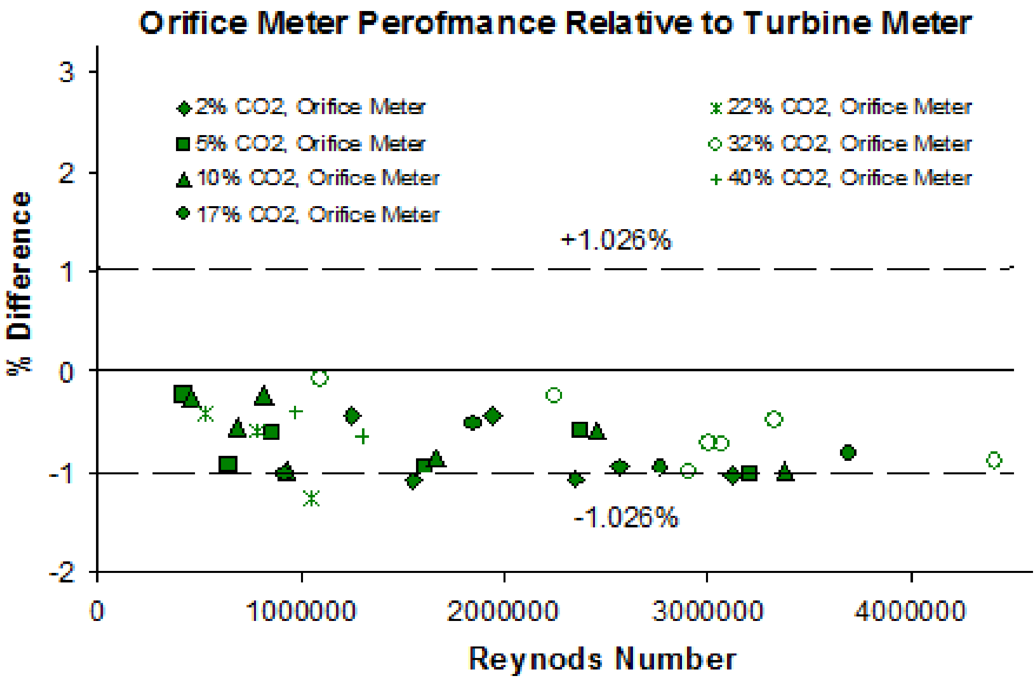

Fig 27. Orifice to Turbine Meter Flow Rate Prediction Comparisons

The tests were conducted at 14 & 49 Bar(a), across 4e5 < Reynolds number < 4.5e6 with CO_2 concentrations in a natural gas of 2% (i.e. baseline), 5%, 10%, 17%, 22%, 32% and 40%. Sample data showing the difference between the orifice meter and the turbine meter is shown in Figure 27. The dashed line represents the root mean square of the two meters' uncertainties (when both meters are operating correctly). The meters agreed within their respective uncertainties to 95% confidence. The two meters, using two different physical principles, tended to agree with each other across the range of CO_2 concentrations tested. Changing the CO_2 concentration had no noticeable effect on the performance of the meters. Hence, despite the aforementioned concerns, these tests suggest that turbine and orifice meters are suitable for use in natural gas and CO_2 up to at least a CO_2 concentration of 40%.

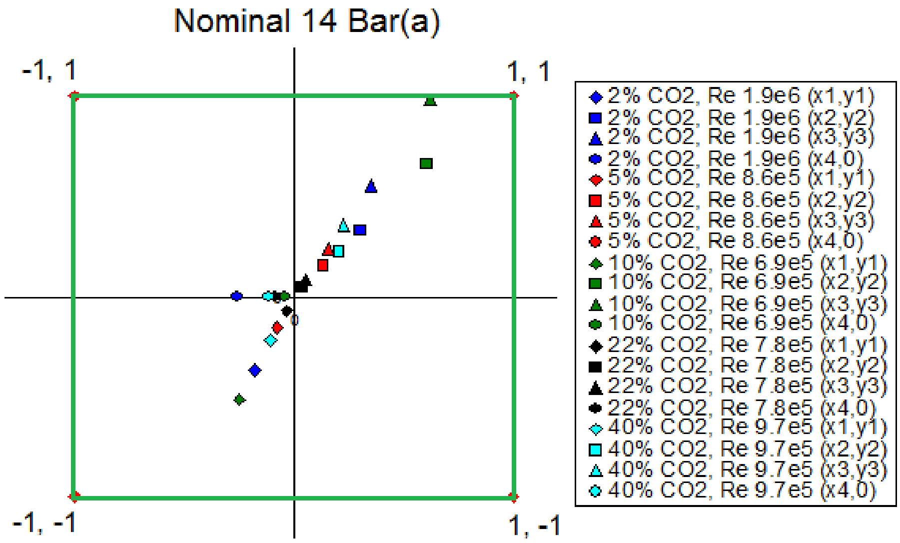

Fig 28. Sample 14 Bar(a) 8", 0.564β Orifice Meter Prognosis Results for Varying CO_2 Concentrations.

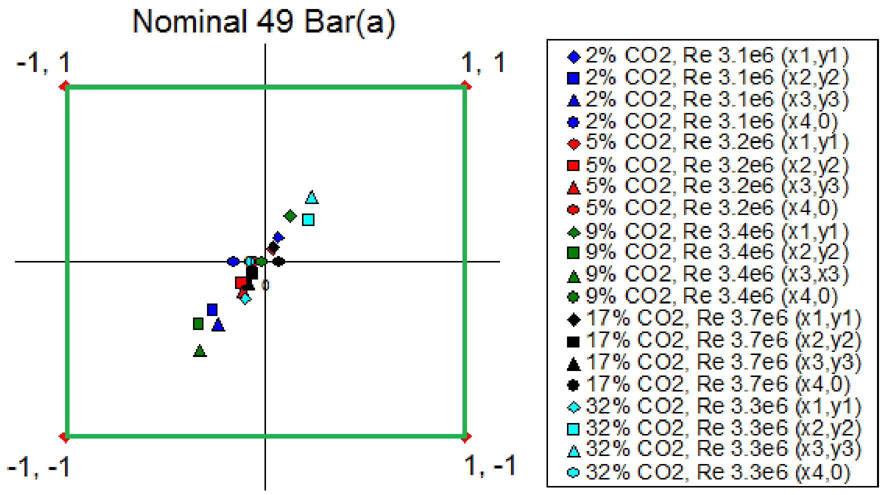

Fig 29. Sample 49 Bar(a) 8", 0.564β Orifice Meter Prognosis Results for Varying CO_2 Concentrations.

Figures 28 & 29 shows sample Prognosis results from the orifice meter. For all data taken, the diagnostic system 'Prognosis' continued to operate normally for natural gas / CO_2 mixture with $CO_2 \leq 40\%$. It is expected that all DP meters would give the same result. Therefore, DP meters used in high CO_2 concentration natural gas flow applications operate to their normal uncertainty and through pressure field monitoring have a fully serviceable diagnostic system.

This project is another example of how DP meter pressure field monitoring has expanded (or at least confirmed) DP meter capabilities.

3.6 Wet Gas Meter Developments (by DP Diagnostics, CEESI & Various Operators)

Many natural gas wells produce wet gas flows. Wet gas flow is an extremely adverse flow condition for any flow meter. However, the sophisticated multiphase wet gas meter technologies are not commercially viable for a huge number of economically marginal fields. Hence, operators seek to compromise between cost and capability by using the gas meter with the best wet gas flow performance.

Like all gas meter technologies DP meters are significantly affected by the presence of liquids with gas flows. However, relative to other gas meter technologies the DP meter is reasonably resistant to the adverse affects of wet gas flow. It is for this reason that virtually all multiphase wet gas meter systems have a DP meter at the core of their design. It is also for this reason that operators chose DP meters for marginal wet gas flow production flows. Hence, multiple operators have approached DP Diagnostics / Swinton Technology regarding the potential of adding pressure field monitoring (i.e. Prognosis) to DP meters as an economically viable alternative to full wet gas metering systems.

Figures 30a & 30b show sample photographs of wet gas flow (moving left to right) from a CEESI view port. Figure 30a shows stratified horizontal flow, where the pressure and gas velocity are relatively low and the phases are separated. Figure 30b shows mist flow, where the pressure and gas velocity are relatively high and the phases are mixed.

Fig 30a. Stratified Flow

Fig 30b. Annular Mist Flow

Figure 26 shows an 8", schedule 40 orifice meter installed in the CEESI wet gas flow facility. Figure 31 shows CEESI sample wet gas flow Prognosis results when this orifice meter had a 0.689β plate installed. As the diagnostics are being used to monitor the level of liquid loading (i.e. Lockhart Martinelli parameter, X_{LM}) this is a trending application and there is no need to normalise the data. Hence, the data is presented as $(\psi\%,\alpha\%)$, $(\lambda\%,\gamma\%)$, $(\chi\%,\eta\%)$ & $(\delta\%,0)$.

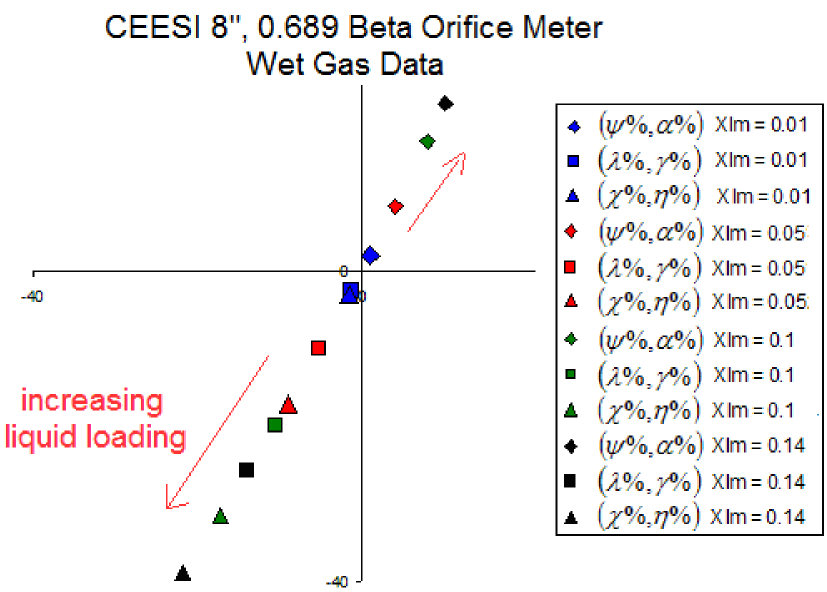

Fig 31. Sample Prognosis Data Plot at 17.2 Bar(a) at 40^{0}C & 26.5 MMSCFD.

$$X_{LM} = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}} \quad \text{--- (5)}$$

Equation 5 defines the Lockhart Martinelli parameter. This is a measure of the liquid content of the wet gas flow. Note that $\dot{m}_g$ & $\dot{m}_l$ are the gas and liquid mass flow rates respectively, and ρ_g & ρ_l are the gas and liquid densities respectively. Figure 31 shows that as the wet gas liquid content increases and decreases the diagnostic points diverge and converge respectively.

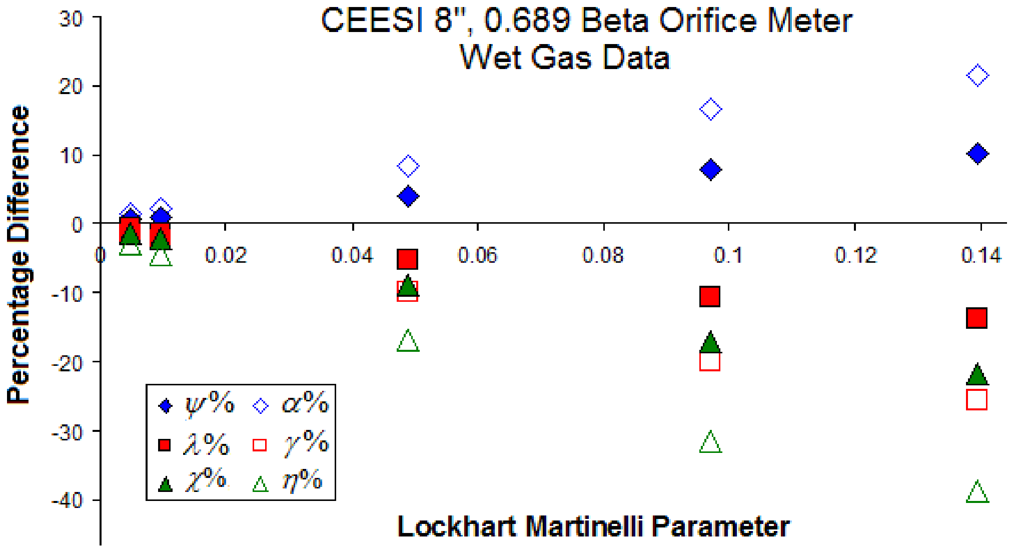

Fig 32. Alternative Prognosis Data Plot at 17.2 Bar(a) at 40^{0}C & 26.5 MMSCFD.

The data presentation in Figure 31 is not the only way the diagnostic output could be presented. The six diagnostics $(\psi\%,\alpha\%)$, $(\lambda\%,\gamma\%)$ & $(\chi\%,\eta\%)$ may also be plotted relative to the parameter being trended; in this case the Lockhart Martinelli parameter. Figure 32 shows CEESI data for 17.2 Bar(a) at 40^{0}C & 26.5 MMSCFD plotted in this way. The data shown in Figure 31 is included in the larger data set shown in Figure 32.

Figure 32 shows the orifice meter Prognosis system's sensitivity to wet gas flow. Each of the six diagnostic parameters are sensitive to changes in the liquid loading. As the Lockhart Martinelli parameter increases so does each diagnostic parameter. Figure 32 also indicates that the six diagnostic parameter vs. Lockhart Martinelli parameter relationships have different gradients. That is, the six diagnostics have different sensitivities to liquid loading changes.

There are dedicated wet gas meter designs that use a Venturi meter in particular, coupled specifically with the PLR vs. Lockhart Martinelli parameter relationship to make a wet gas liquid loading monitor. The PLR vs. Lockhart Martinelli parameter relationship for this orifice meter is shown in Prognosis via $\alpha\%$. For the case of applying Prognosis to orifice meters, whereas the parameter $\alpha\%$ is clearly sensitive to liquid loading, it is not the most sensitive, and therefore not the most useful of the diagnostic parameters for monitoring liquid loading. The most sensitive, and therefore most useful of the orifice meter diagnostic parameters for monitoring liquid loading are the DP ratios related to the recovered DP, i.e. $\gamma\%$ & $\eta\%$. These two parameters are not only more sensitive to small changes in orifice meter liquid loading than the other parameters (including $\alpha\%$, i.e. the PLR), but also continue to see changes in liquid loading until higher Lockhart

Martinelli parameters, when the other parameters have gradually become insensitive to the increasing amounts of liquid. Therefore, orifice meters with pressure field monitoring software have been shown to be capable of monitoring changes in wet gas flow liquid loading up to moderate liquid loadings. The Prognosis system's use of alternative DP ratios to the standard singular PLR method used in some Venturi wet gas meter designs has been shown to be advantageous to orifice meters in wet gas flow service.

Steven et al [9] reports in detail on the subject of wet gas flow orifice meter pressure field monitoring research. This project is yet another example of how DP meter pressure field monitoring has expanded DP meter capabilities.

4 RUSSIAN GOST APPROVAL FIELD TRIALS

As part of the process to attain GOST approval in Russia, STP & IMS organised a Prognosis trial at the ConocoPhilips / Rosneft Polar Lights field. The test meter was a 4" paddle plate orifice meter in a flare gas application (see Figure 33). The available downstream tap was at 6.9D downstream of the plate, i.e. 0.9D downstream of the ideal location. The standard correction factor for the excess pipe length was applied, with an assumption made that the inside pipe condition was typical good quality pipe roughness. The Prognosis software was expanded to include the GOST orifice meter coefficients. The meter under test was assumed to be fully serviceable.

Fig 33. Polar Lights 4" Paddle Plate Orifice Meter with Diagnostics Installed.

Testing took place in January 2014. The Prognosis software received from the flow computer the listed meter geometry (of inlet diameter of 102.26mm and orifice diameter of 44.45mm). The pressure of 2.4 Bar(a) and temperature of 71^0C produced a gas density of approximately 2 kg/m^3. The Prognosis operators chose to set the sensitivity to x = 1%, y = 2.5%, z = 2.5%, a = 3%, b = 3.5%, c = 4.5%, d = 1%. Figure 34 shows the initial Prognosis response.

The diagnostics indicated a significant error. The DP check was indicating the DP readings were correct. A list of potential problems that could cause that diagnostic pattern was listed. This included the comment that the orifice diameter may actually be lower than stated in the calculations. The plate was pulled and measured. It was discovered that the true inlet diameter was not 44.45mm as stated in the flow computer, but 38.1mm (i.e. the true beta was 0.3726, not the stated 0.4347).

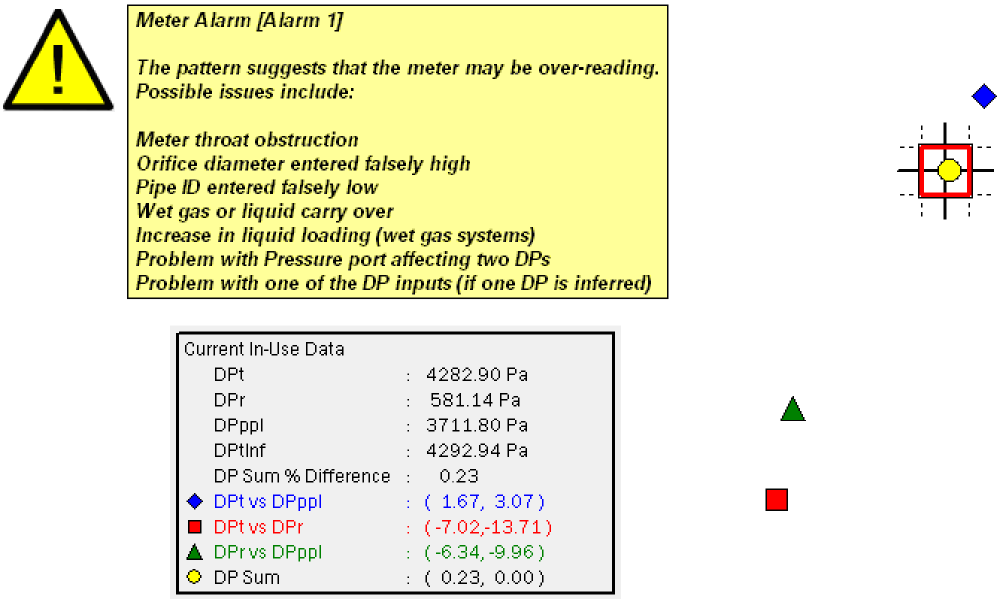

Fig 34. Prognosis Response at Polar Lights with Flow Computer Geometry Used.

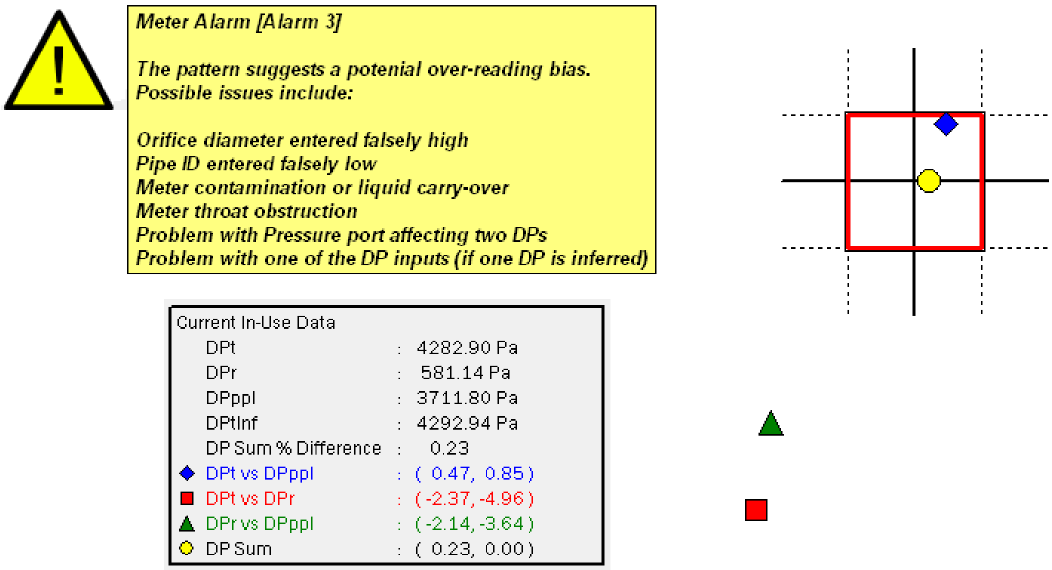

Fig 35. Prognosis Response at Polar Lights with Corrected Geometry Used.

The archived Prognosis data was re-run using the correct orifice diameter. Figure 35 shows the shift in the diagnostic response. Although the diagnostics points are now much closer to the origin there is still a clear alarm that the meter has a significant problem. The operator therefore checked the meter run. Figures 36 & 37 show the views looking upstream & downstream respectively.

The meter run is clearly not compliant with ISO 5167 nor GOST. There is significant weld beads and rust throughout the run. This will cause flow disturbance. DP Diagnostics has tested the effects of flow disturbances on orifice meters (e.g. Steven [2]) and the diagnostic plots presented are very similar to the pattern shown in Figure 35. The diagnostics were correctly indicating that the meter still had a problem.

Fig 36. Upstream Meter Run

Fig 37. Downstream Meter Run

DP Diagnostics and Swinton Technology noted that this particular problem had not been included in the list of potential problems offered with that diagnostic alarm. With previous test data showing this result (Steven [2]) this was an over-sight and this problem will now be added to the software's list of potential problems.

The field test of Prognosis had been successful, if not in the way originally planned. IMS continued to monitor the meter's diagnostic response which subsequently demonstrated consistency in the Prognosis output.

5 DEVELOPMENTS IN DP METER PRESSURE FIELD MONITORING - DYNAMIC RESPONSE

The present DP meter diagnostic suite does not directly monitor the time dependent response of the DP signals and the associated diagnostic parameters. The present diagnostics compares either a single result, or a time averaged result from a given set of results recorded over a given period of time, to the fixed expected (calibration or standard) baseline. Time is only considered in the present DP meter diagnostic suite in two indirect ways:

- the averaging of multiple inputs read over a set span of time to give a single averaged diagnostic output, or,

- the act of the operator manually playing back, in chronological order, the archived individual diagnostic results in order to check for trending.

However, there is further valuable information imbedded in monitoring the three DPs and the associated seven diagnostic checks relative to time. That is, there is value in monitoring both the instantaneous (or averaged) 'static' pressure field diagnostic output (as is presently done) and the time dependent 'dynamic' response of the pressure field diagnostic output. This additional DP meter diagnostic approach can produce further discrimination regarding what adverse operating conditions the DP meter may be exposed to.

Monitoring the DP meter's pressure field 'dynamic' fluctuations is analogous to the USM's 'turbulence' diagnostics. These USM diagnostics monitor the standard deviation (or 'stability') of that meter's primary signals, i.e. the variation in time measurements. Likewise, DP meter 'turbulence diagnostics' is the monitoring, cross referencing and analysis of the standard deviation (or 'stability') of that meter's primary signals, i.e. the read DPs, and the associated diagnostic parameters.

The DP meter turbulence diagnostic technique is different to the existing DP meter diagnostic techniques in one *very* significant aspect. The existing diagnostics (reviewed in Section 2) could be described as "absolute diagnostics". Here, the meter output is compared to either a particular physical law, or, a calibration result that is guaranteed to low uncertainties to be the performance characteristic of the correctly operating meter system in the field. Either the metering system output is shown to agree with physical law and / or the guaranteed calibration results, or it does not agree. There is nothing subjective about this type of diagnostic check. It is an absolute pass or fail statement irrespective of any operator's opinion. However, the DP meter turbulence diagnostic methodology does not fall into this category.

The DP meter turbulence diagnostic methodology could be described as a "relative diagnostic" method. Here, the system output is compared to the historical system output. There is no output guarantee fixed by either a particular physical law, or by any applicable laboratory calibration result. Unlike absolute diagnostics, relative diagnostics are subjective. Primary DP signal turbulence levels differ (by small to moderate amounts) for different DP flow meters and DP transmitters. Normal turbulence levels for one meter system is not necessarily normal turbulence levels for another nominally identical metering system, even in the same application. If a DP meter has DP signal turbulence levels calibrated at a laboratory, even when using the same DP transmitters the operator has no absolute guarantee that these levels will be representative of the correctly operating meter in the field. Many influences can affect the correctly operating system's DP signal standard deviation, such as different DP transmitters, slight differences in the pipe work etc. The DP meter turbulence diagnostic concept must have its baseline set by recording the values across a known period of actual meter operation in service. This subjective diagnostic method is therefore comparing the relative turbulence of 'then and now', which is of course different to the absolute diagnostics comparing precise performance characteristics to absolute known performance requirements.

The DP meter turbulence diagnostic method is an eighth DP meter diagnostic check. Unlike the existing seven diagnostics it is subjective, but it does give the meter operator extra useful information. Furthermore, by cross referencing this relative diagnostic method with the existing diagnostic suite it is possible to further distinguish between certain types of DP meter malfunction. The following is a discussion on the DP meter turbulence diagnostic method development and operation.

5.1 Pre-Existing DP Transmitter Internal Diagnostics

Most DP transmitters have internal diagnostics. These diagnostics monitor the health of that DP transmitter. However, they are isolated to that DP transmitter. Multiple DP transmitters on a single DP meter do not presently communicate diagnostic results to each other, and they do not give any information with regard to the health of the DP meter system as a whole.

No industrial flow application produces a truly steady flow. Flows that are normally considered 'steady' have line pressures that vary only very slightly around an average value. The line pressure is typically significantly larger than the DPs produced by a DP meter. Therefore, even a slight rise and fall of pressure over time means that static pressure at each DP meter pressure port rises and falls significantly compared the DP being measured. With normal operation this has no adverse effect as all the meters' pressure ports have the same synchronized rising and falling line pressure. Figure 38 (simplified and exaggerated for clarity) shows a representation of this phenomenon. The high and low pressure values at the meter's ports fluctuate in phase with the line pressure and a relatively steady DP with a low standard deviation is read. Figure 39 shows the effect of a pressure port becoming blocked, sealing the fluid in the impulse line at the pressure from when it was sealed. In the example shown in Figure 39 the low pressure port is blocked. The resulting DP reading no longer has the two ports' pressure variations cancelling out. Therefore, the DP's standard deviation becomes significantly higher.

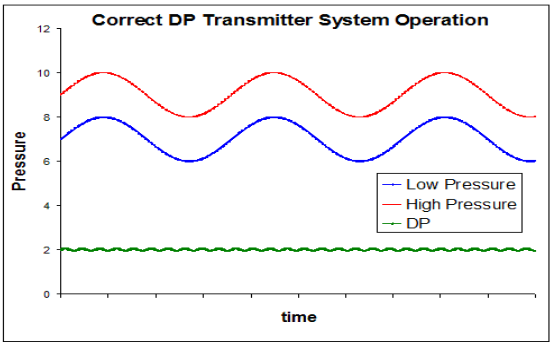

Fig 38. Standard DP Reading.

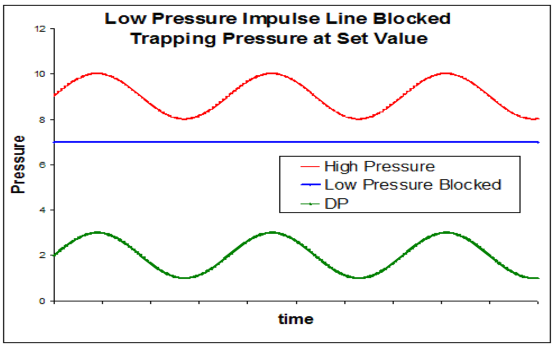

Fig 39. DP Reading with Blocked Port.

Modern DP transmitters compare actual to historical DP standard deviations to monitor for blocked impulse lines. This is a relative diagnostic check. There are various descriptions of this technique available in the literature (e.g. Wehr [10]). When a significant shift in standard deviation is noted, software in the DP transmitter head can check the individual pressure readings. Relative to each other, the more stable pressure signifies a blocked impulse line and the more unstable pressure signifies a clear impulse line. However, when a pressure port is noted as blocked these internal diagnostics cannot tell the operator the correct DP.

A variant of the stand alone DP transmitter standard deviation diagnostics is the use of the single DP standard deviation to monitor wet gas flow. Because wet gas flow increases the standard deviation of a DP meter's DP readings, various projects have investigated this. For example, Wehr [11] assumed wet gas flow from the outset, significantly increased the frequency of the DP readings and attempted to relate the single DP transmitter's standard deviations to the wet gas liquid loading.

5.2 New Developments in DP Meter DP Signal Analysis Diagnostics

5.2.1 DP Meter Turbulence Diagnostics & Identifying Blocked Impulse Lines Theory

The present DP meter diagnostic suite gives a generic alarm when an impulse line is blocked and the pressure in the impulse line is not representative of the pressure being produced by the pressure field. However, they do not specifically point to that particular problem being the cause of the alarm. The following discussion explains how that can be achieved. Figure 40 shows a simplified theoretical comparison between the three DP fluctuations if the DP meter with a downstream pressure tap is fully serviceable, and when each one of the impulse lines / ports becomes blocked. Moving clockwise around the graphs in Figure 40 shows the effect on the DP readings if for 'steady flow' the upstream, downstream or mid-stream (or 'throat') impulse lines become blocked. The top left graph shows that the three DP readings have relatively small DP standard deviations (i.e. fluctuations) when the single phase flow DP meter is fully operational. The other graphs show that when one impulse line is blocked the two DP transmitters sharing that impulse line will, due to the effect shown in Figure 39, have a significantly increased DP standard deviation. The DP transmitter that does not utilise the blocked impulse line has no change in DP standard deviation. By comparing the relative DP standard deviations it is possible to identify that a particular impulse line may be blocked.

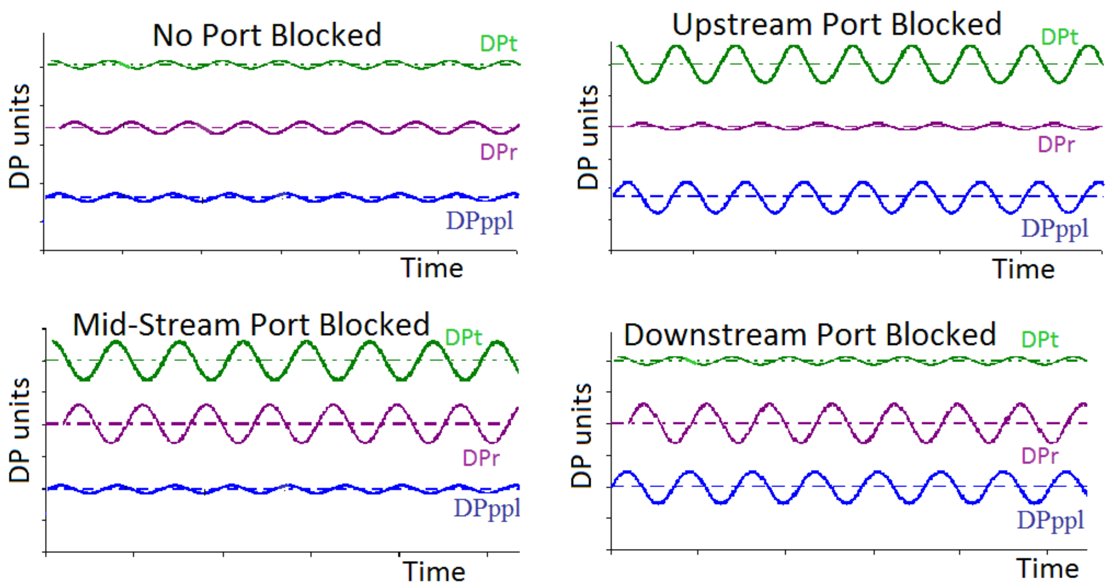

Fig 40. DP Transmitter Responses to Clear & Blocked Impulse Line Combinations.

No internal diagnostics to individual DP transmitters are being used. Prognosis can read the three individual raw DP outputs (of DP transmitters with or without internal diagnostics) and inter-compare the three DP reading standard deviations. This is the inter-comparison of multiple DP transmitter information that has traditionally been kept isolated. This technique can identify a blocked impulse line. By identifying which impulse line is blocked the system also identifies which two impulse lines are serviceable. The associated read DP is confirmed as still valid. Through the appropriate flow equation (see equation set 2 through 4) the flow rate can be predicted. Traditionally, even with modern DP transmitter internal diagnostics, an identified blocked impulse line means the single DP reading is found untrustworthy and the meter system is out of service. This system will allow the meter to continue to operate until maintenance can be carried out.

5.2.2 DP Meter Turbulence Diagnostics & Identifying Wet Gas Flow

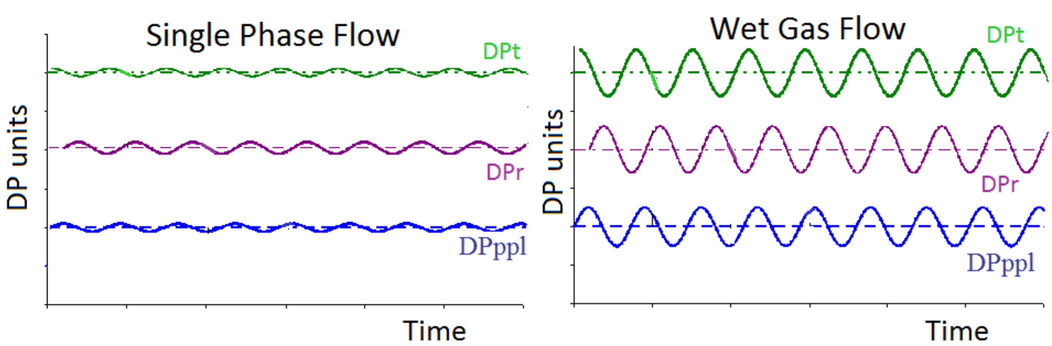

Fig 41. DP Transmitter Responses to Dry & Wet Gas Flow.

The present DP meter diagnostic suite gives a generic alarm when the gas is wet. However, they do not specifically point to wet gas flow being the cause of the alarm. Figure 41 shows a simplified theoretical comparison between the three DP fluctuations if the DP meter is encountering dry or wet gas flow. Wet gas flow causes **all** DP readings to have an increase in standard deviation. A DP meter could identify wet gas flow by comparing the present three DP reading standard deviations to historical dry gas flow baseline data. This then, is a relative diagnostic check.

Figure 40 shows the effect on the three DP reading standard deviations if there is a blocked impulse line. Only two of the three DP readings have increased standard deviation. The effects a blocked impulse line and a wet gas flow have on the three DP standard deviations are different and therefore the DP meter relative turbulence diagnostic check could distinguish between the two.

5.2.3 DP Meter Turbulence Diagnostics Test Meter Data

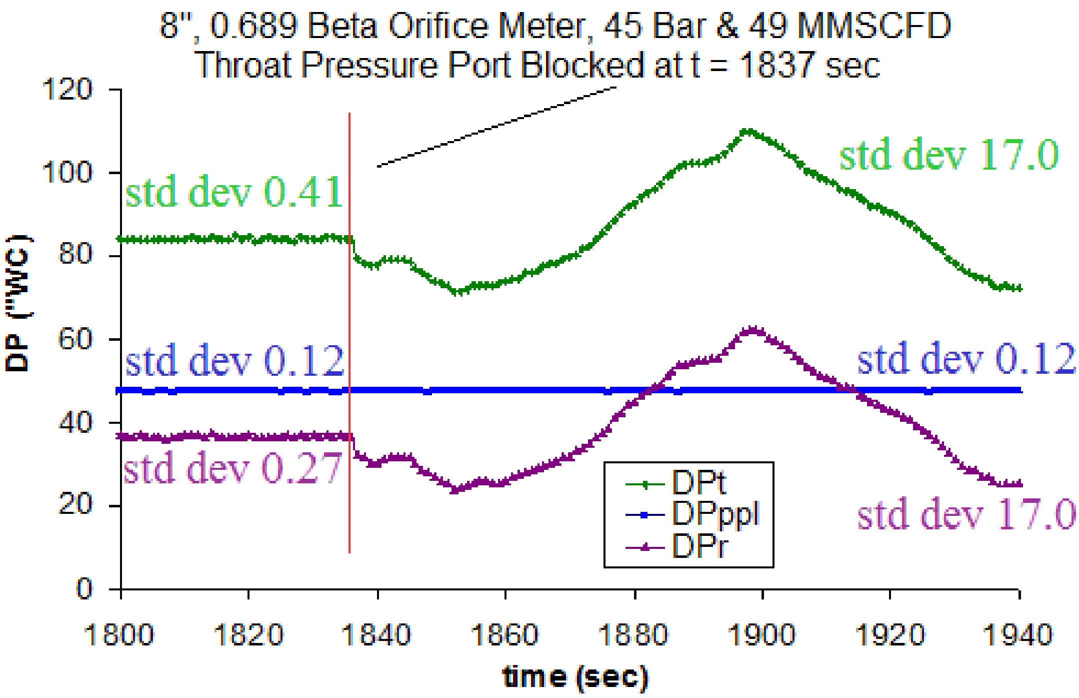

Fig 42. Orifice Meter Response to Blocked Mid-Stream ("Throat") Impulse Line.

A CEESI 8", 0.68β orifice meter (see Figure 26) was in use with dry natural gas flow at 45 Bar(a) flowing 46 MMSCFD. The traditional, recovered and PPL DPs were read at approximately 84"WC, 38"WC & 46"WC. The standard deviations of these DPs were approximately 0.41, 0.27 & 0.12 respectively. This is shown in Figure 42. Then, at 1837 seconds into the data logging sequence the low pressure port (i.e. the mid-stream pressure port) was blocked by the shutting of a valve on that impulse line. The resulting effect is very obvious. The PPL DP continues to read the same DP at the same low standard deviation. The other two DPs begin to have drifting DPs (that follow the small natural line pressure fluctuation) and their respective standard deviations significantly increase to 17.0. When allowing for the fact that Figure 40 assumed a DP meter like a Venturi meter where the $DP_r > DP_{PPL}$ and the orifice meter under tests has the opposite, i.e. $DP_r < DP_{PPL}$, Figure 42 shows the same reaction as expected for the blocked low pressure / midstream pressure port. The maximum & minimum variation of the traditional DP around the correct value of 84"WC is approximately 115"WC, which is a difference of +31"WC / +0.077 Bar, i.e. a line pressure variation of < 0.2%. The DP meter turbulence diagnostic method is very sensitive to blocked impulse lines.

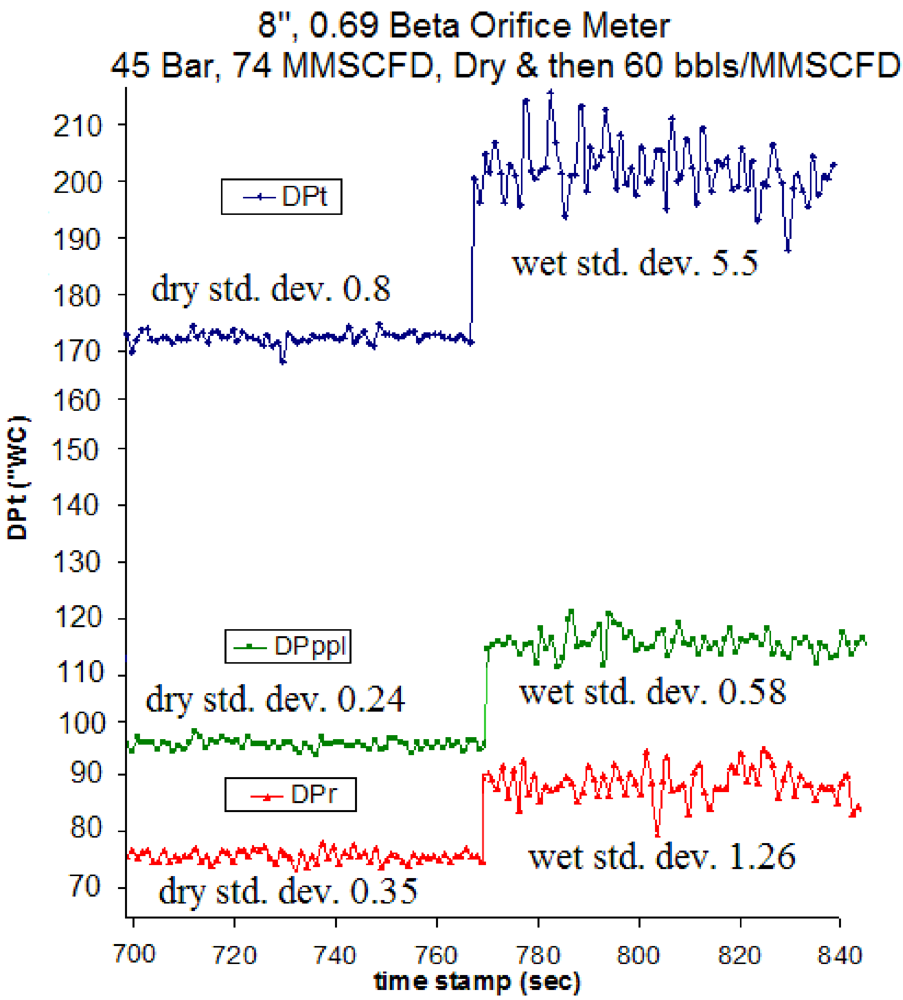

Fig 43. Orifice Meter Response to Wet Gas Flow.

The same CEESI 8”, 0.68β orifice meter (see Figure 26) was tested with dry and wet natural gas flow. Figure 43 shows data at 45 Bar(a) & 74 MMSCFD. With dry gas the traditional, recovered and PPL DPs were read at approximately 172”WC, 96”WC & 76”WC. The standard deviations of these DPs were approximately 0.8, 0.24 & 0.35 respectively. This is shown in Figure 42. Then, at 770 seconds into the data logging sequence the liquid was injected at a rate of 60 bbls/MMSCFD (i.e. X_{LM} of 0.12). As expected the DPs increased. With this wet gas flow the traditional, recovered and PPL DPs were read at approximately 203”WC, 87”WC & 116”WC. The standard deviations of these DPs were approximately 5.5, 1.26 & 0.58 respectively. This is also shown in Figure 42. Again, when allowing for the fact that Figure 41 assumed a DP meter like a Venturi meter where the $DP_r > DP_{PPL}$ and the orifice meter under tests has the opposite, i.e. $DP_r < DP_{PPL}$, Figure 43 shows the same reaction as expected for the blocked low pressure / midstream pressure port. The DP meter turbulence diagnostic method is sensitive to, and can potentially identify wet gas flow.

For all the DP meter turbulence diagnostic method can potentially identify wet gas flow, this relative diagnostic check is certainly is not as powerful as an absolute diagnostic check. Examples of the standard diagnostics reaction to wet gas flow are shown using data from this same 8” orifice meter in Section 3.5’s Figures 31 & 32. Wet gas produces a strong diagnostic pattern that can be recognised as such. However, as this pattern is not unique to wet gas flow (i.e. there are a few meter malfunctions that can cause this pattern) and the addition of the DP meter turbulence diagnostic method can help identify wet gas flow.

If the operator was to use this relative check alone it is subjective if this is wet gas flow. Notice, that although all three DP values and their standard deviations rose, not all three DPs had similar increases in standard deviation. Whereas the traditional DP's standard deviation increased five fold, and the recovered DP standard deviation quadrupled the permanent pressure loss increased by just two and a half times. If there was no set of absolute diagnostic checks (i.e. the main diagnostics) with which to cross reference, would an operator truly see wet gas here? Or would the operator see a much bigger standard deviation on the traditional and recovered DPs compared to the PPL and falsely assume the relative check is showing a blocked mid-stream / throat impulse line? This is an example of the reactive diagnostic check methods being subjective. Here, however, we can cross reference this relative check with absolute diagnostic checks. This means we can be reasonably confident of the correct prognosis.

5.2.4 Orifice Meter Turbulence Diagnostics Field Data

ConocoPhillips (CoP) installed two Prognosis systems on the Jasmine development. The first system was installed on a 12", 0.636β orifice meter with a downstream pressure tap 10D downstream of the plate. This first meter was installed on the gas flow leg out of the test separator. The sample data shown here from this meter had a pressure of 62.5 Bar(a), a temperature of 117^{0}C, and a gas density of 44.4 kg/m^3. The second system was installed on a 24", 0.622β orifice meter with a downstream pressure tap 8D downstream of the plate. This second meter was installed on the gas flow leg out of the HP test separator. The sample data shown here from this meter had a pressure of 41 Bar(a), a temperature of 102^{0}C, and a gas density was 30.0 kg/m^3. Both orifice meters read the traditional & recovered DPs only. The PPL was inferred meaning the DP check diagnostic was not available. The standard appropriate correction factors for the non-standard downstream pressure tap locations were applied. Due to the high temperature expected ConocoPhillips knew both meters would be metering light water loading wet gas flows. The water content was captured using the Antoine calculation within the flow computer.

Figures 44 & 45 show sample Prognosis results from the 12" and 24" orifice meters respectively. The Prognosis output is usually averaged over a period of time to give a clean result. In both these examples the sample data sets were recorded once a minute for three hours. The averaged results are shown on the left. The right hand graphs are the 180 individual results plotted together. Here we see that the minute by minute points are not even approximately steady. The averaged data gives a wet gas over-reading pattern as expected. But the averaging of the data gives perhaps a false view of the stability of the flow. It is only when looking at the 'raw' un-averaged minute by minute data that the unsteadiness of the diagnostic output becomes apparent. There are other orifice meter malfunctions that can cause a similar averaged diagnostic result (e.g. incorrect geometry keypad entry), but these tend to produce a pseudo-steady Prognosis response. The unsteadiness of this response is a strong marker of wet gas flow.

The Prognosis co-ordinates are relatively unsteady because the DPs being read from the orifice meter are relatively unsteady, i.e. have a relatively high standard deviation. The traditional & recovered DP are not read at exactly the same time during each data sweep, so the out of phase nature of the DP readings coupled with the fact that both DPs have relatively high fluctuations gives this unsteady result. Note that the progressive data sweeps produced plots randomly in the spread of the data. There was no obvious time dependent pattern to the data.

Figure 46 shows the 24”, 0.622β Orifice Meter HP Separator Gas Outlet DP Stability. Note the DPs are relatively unsteady (as shown in Figure 43 for sample laboratory data). If data acquisition was faster here a more rapid DP bounce would be revealed.

This CoP Jasmine data shows the principle of DP meter turbulence diagnostic method in practice. DP Diagnostics and Swinton Technology will be adding this patent pending eighth DP meter diagnostic check to the next edition of the DP meter diagnostic software ‘Prognosis’.

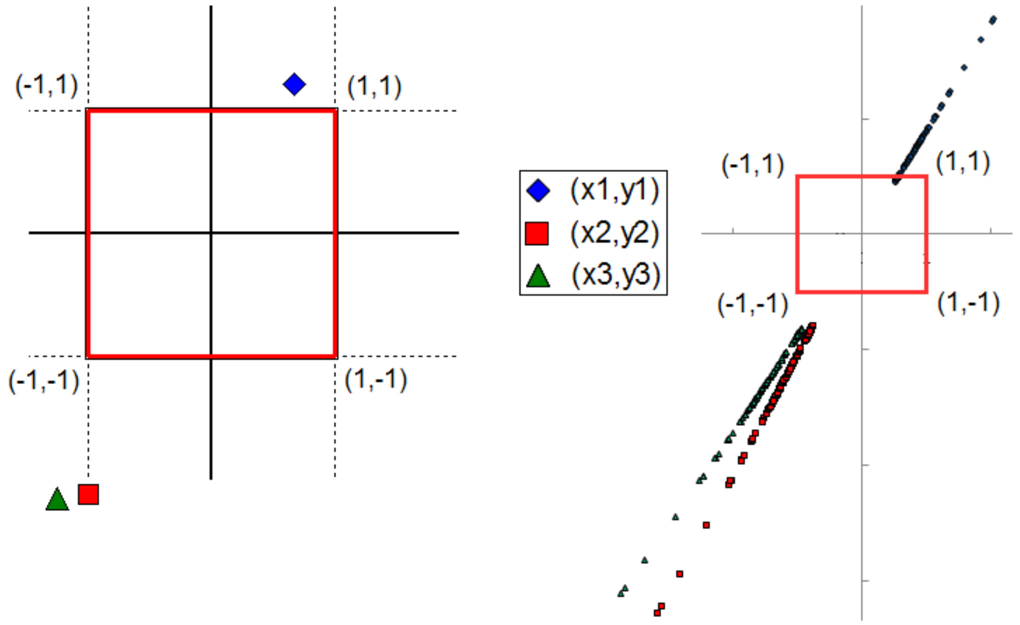

Fig 44. Jasmine 12”, 0.636β Orifice Meter Test Separator Gas Outlet Diagnostics.

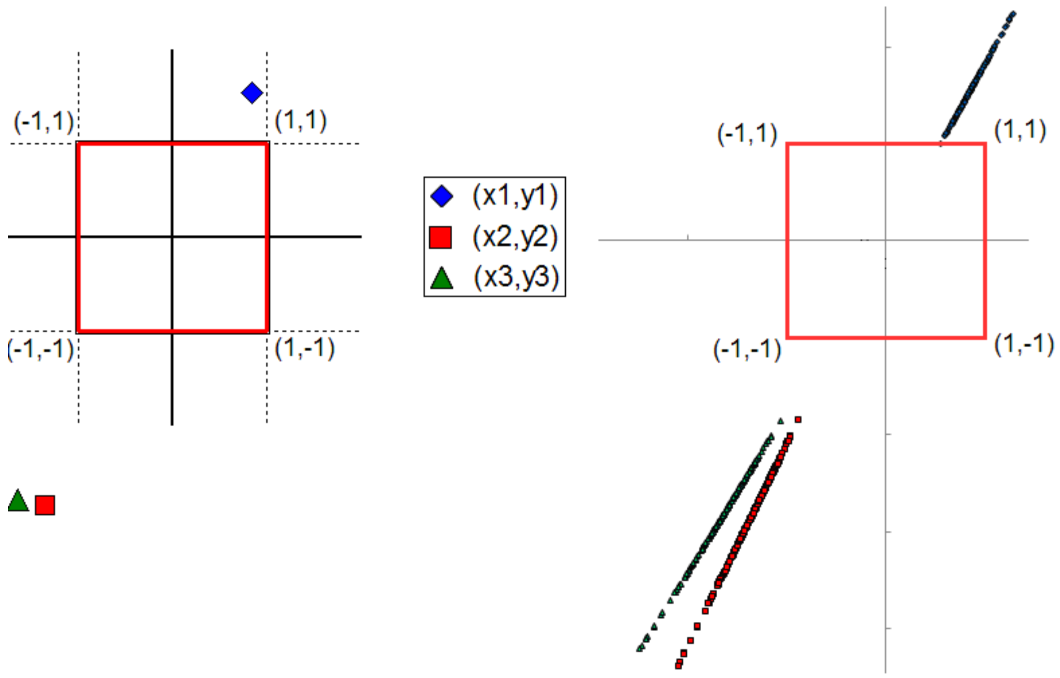

Fig 45. Jasmine 24”, 0.622β Orifice Meter HP Separator Gas Outlet Diagnostics.

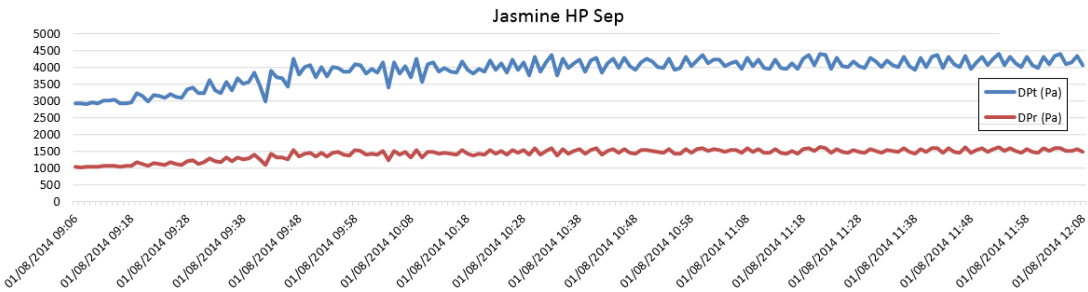

Fig 46. CoP Jasmine 24", 0.622β Orifice Meter HP Separator Gas Outlet DP Stability.

5.2.5 Venturi Meter Turbulence Diagnostics DP Diagnostics / CEESI Laboratory Data

Figure 47 shows a DP Diagnostics 6", 0.7β Venturi meter undergoing dry and wet gas flow testing at CEESI. Flow is from right to left. Note the three pressure ports and three DP transmitters. This CEESI test facility logged data once every six seconds.

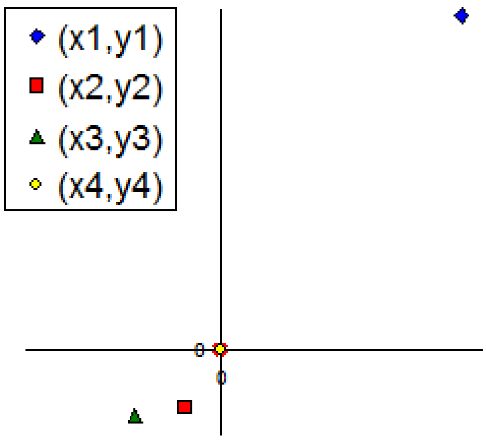

Fig 47. 6",0.7β Venturi Meter at CEESI Wet Gas Loop, with Prognosis Result.

For a pressure of 35 Bar and a gas flow rate of 4.33 kg/s, Table 3 shows the traditional, recovered and PPL DP averaged values taken from dry and wet gas flow five minute (50 data point) tests. The DP standard deviations for both dry and for wet gas flow are also shown. The wet gas flow had a Lockhart-Martinelli parameter of 0.1 (which is in this case a liquid flow of 2.34 kg/s), which is a GVF of 98.2%.

Lockhart-Martinelli Parameter (X_{LM})	0 (Dry)	0.1 (Wet)
Traditional DPt (kPa)	4.752	7.086
Standard Deviation of DPt (%)	0.142	**1.062**
Recovery DPr (kPa)	4.405	3.912
Standard Deviation of DPr (%)	0.154	**3.158**
PPL DPppl (kPa)	0.353	3.189
Standard Deviation of DPppl (%)	0.951	**2.448**

Table 3. DP Diagnostics 6", 0.7β Venturi Meter Data from CEESI Flow Tests.

Figure 47 shows the standard Prognosis response to wet gas flow. The diagnostics are so sensitive to this moderate wet gas flow through a Venturi meter that the NDB is shrunk to a dot on the origin. The liquids presence causes the DPs to change and substantially increases all three DP standard deviations. This is an example of the Venturi meter DP standard deviations reacting to wet gas flow in a similar way to the orifice meter (e.g. see Figure 43). This is another example of DP meter turbulence diagnostics. The existing diagnostic result in Figure 47 is averaged data and the pattern is the pattern produced by wet gas. However, the pattern is not unique to wet gas flow. There are a few other problems that could cause such a pattern. However, wet gas has the added signature of high standard deviation DPs. By combining the existing diagnostic suite and DP meter turbulence diagnostics it is possible to identify wet gas as the more likely causes of the issue than issues that create relatively stable DPs.

However, just as was shown for the orifice meter, if the operator was to use this relative check *alone* it is subjective if this is wet gas flow. As with the orifice meter example all three Venturi DP standard deviations rose, but they did not have proportional increases. The traditional DP's standard deviation increased seven fold, the recovered DP standard deviation increased twenty fold, but the PPL standard deviation only slightly more than doubled. If there was no set of absolute diagnostic checks (i.e. the main diagnostics shown in Figure 47) with which to cross reference, would an operator truly see wet gas here? Or would the operator see a much smaller standard deviation on the PPL DP and falsely assume the relative check is showing a blocked mid-stream / throat impulse line? This is another example of the reactive diagnostic check methods being subjective. With Prognosis, however, we can cross reference this relative check with absolute diagnostic checks. This means we can be confident of the correct diagnosis.

5.2.6 Comparing Wet Gas & Blocked Impulse Line DP Standard Deviations

Section 5.2.3 showed the response of an 8", 0.689β orifice meter to a blocked impulse line (see Figure 42) and a wet gas flow (see Figure 43). It was then shown that if the DP meter turbulence diagnostic method was applied alone (without cross referencing this diagnostic with the existing diagnostic suite) it may be difficult to distinguish between a rise in DP standard deviations due to wet gas flow and due to a blocked impulse line. It is by cross referencing the existing diagnostic suite with this DP meter turbulence diagnostic method that produces a genuine advance. However, there is one other analysis technique that could improve the DP meter turbulence diagnostic method here. That is, take account of not just the relative magnitude of the 3 DP standard deviations but also the period of these DPs fluctuation.

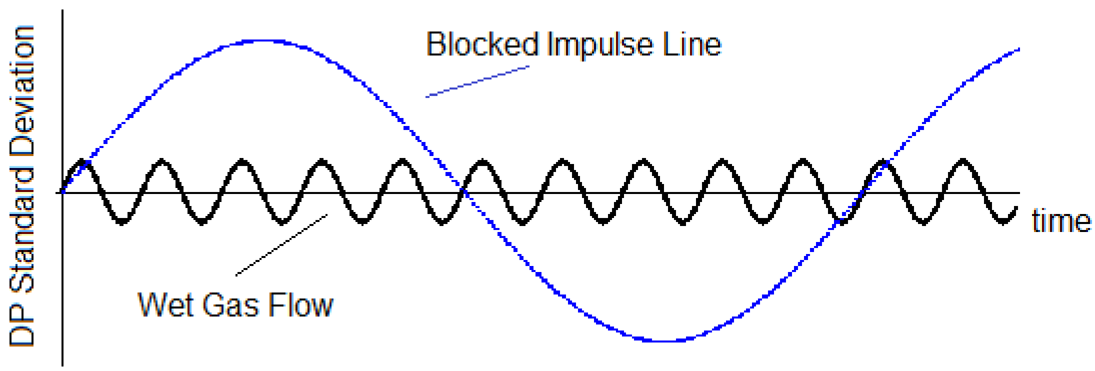

Fig 48. Different DP Meter Problems Produce Different DP Fluctuations.

Most relatively steady gas flows have a line pressure that can rise and fall by a fraction of a percent over time. This variation in pressure is usually a long period / low frequency phenomenon that produces a relatively large DP fluctuation. Therefore, if a DP meter impulse line is blocked the variation in DPs associated with that impulse line will have a corresponding relatively large magnitude low frequency / long period fluctuation. Most relatively steady wet gas flows have DPs that rise and fall by a few percent over time. This DP variation is caused by the relatively chaotic flow. This variation in DP is therefore a relatively small magnitude short period / high frequency phenomenon. This phenomena is evident when comparing Figure 42 for a dry gas blocked impulse line and Figure 43 for wet gas flow. Figure 48 shows a sketch highlighting this point. As this DP meter turbulence diagnostic method develops, the frequency / phase information can be taken into account to help distinguish between different problems.

DP meter turbulence diagnostics that monitor not just the magnitude of the DP signal standard deviations, but also other information such as the period of the fluctuations, have an analogy with multiphase meter designs that use artificial intelligence / neural networks (e.g. Toral [12]). There is no technical reason why similar artificial intelligence / neural networks could not be developed for single phase meter diagnostics. However, there is a law of diminishing returns. Such a development would take a very considerable undertaking in time and in R&D costs and likely result in real but marginal gains in diagnostic prediction power. Currently DP Diagnostics and Swinton Technology are concentrating on simpler direct analysis of DP signal fluctuations as it has been shown that such a development offers an immediate and significant increase in the diagnostic suite's capability.

6 CONCLUSIONS

DP meter diagnostics based on pressure field monitoring is now becoming widely accepted by the natural gas production industry. As a result of this the software 'Prognosis' is now used by multiple operators and is being tested by 3rd parties, including STP & IMS in Russia.

Industry is now becoming comfortable enough with the pressure field monitoring concept that it is not only being considered for generic DP meter diagnostics but also for developing new DP meter capabilities. In the last three years DP meter pressure field monitoring has been researched, and proven useful, for use with various adverse flow conditions that are traditionally challenging for all flow meter technologies. These research projects include the use of DP meters with pressure field monitoring to monitor:

- contamination levels of DP meter runs,
- erosion levels on multiphase meters,
- oil with water flow metering,
- heavy oil (high viscosity) flow,
- high content CO2 natural gas / CO_2 mixtures, and
- wet gas flow.

The existing generic DP meter pressure field monitoring diagnostic suite is a very capable diagnostic tool. This existing diagnostic suite (without DP meter turbulence diagnostics) allows the system to identify a DP meter malfunction. The particular diagnostic pattern (i.e. combination of all diagnostic results together) which shows a meter malfunction also allows a 'short list' of potential problems to be produced, whilst discounting the malfunctions that could not produce that pattern. DP Diagnostics and Swinton Technology are continuing to develop and strengthen this diagnostic system. The addition of DP meter turbulence diagnostics will allow further discrimination of the diagnostic result. The present short list of possible malfunctions that could produce that diagnostic pattern will be further reduced as DP meter turbulence diagnostics rule out certain possibilities on that list and highlights others as still possible.

DP meter diagnostics have advanced significantly over a relatively short period of time. However, the possibilities offered by pressure field monitoring are so wide and diverse that it is expected that the DP meter diagnostic suite will continue to expand and improve steadily for the foreseeable future.

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