North Sea Flow Measurement Workshop
22-24 October 2018

Technical Paper

A Gran Chimera? Flowrate Prediction Biases of a Malfunctioning Orifice Meter Calculated in Real Time via Internal Meter Diagnostics

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1 INTRODUCTION

This paper discusses the development of the capabilities of an orifice meter verification system. The DP Diagnostics verification system uses a downstream pressure tap (e.g. see Figure 1) to access the information contained within the meter's entire pressure field. An automated system has been developed to state in real time when the meter has a problem, and then by use of pattern recognition to state what that problem is, or short list the possible problems. For many common orifice meter malfunctions, the system is now developed to also estimate the associated flow prediction bias in real time. The benefit of such additional information to flow meter 'terotechnology', i.e. the optimization of flow meter maintenance and operation, as well as supporting audits, and lost and unaccounted for product calculations etc., are self evident.

2 FLOW METER VERIFICATION SYSTEM INDUSTRIAL BENEFITS

Fig 1. 8", Orifice Meter with Downstream Pressure Tap.

As with all industrial equipment, flow meters of all designs should be monitored throughout their life, maintained, and when necessary repaired. However, although central to the operator's relationship with the flow meter, mundane and annoying maintenance is a matter most would rather not think about. Most would rather 'fit and forget'. Indeed considering the importance of correctly predict flow rates, it is stiking that flow meter maintenance is seldom the topic of flow meter technical papers – and there is rarely, if ever, a 'meter maintenance' session at flow meter conferences.

Nevertheless, an old engineering adage holds true for flow meters: 'the problem with maintenance is its importance only becomes visible when it is lacking'. Hence, meter users are grudgingly forced to budget for maintenance, although the subject is not generally considered exciting or conversation worthy.

The inventing and design of flow meters is concentrated in a few places (by design engineers), the making of these designs a little more dispersed (by manufacturing engineers), but the subsequent use of these flow meters is spread over vast and varied applications amongst different companies, different regions, and different industries. And maintenance is almost as widely distrubuted as use. Hence, as a consequence, maintenance and repair are the most widespread forms of flow meter technical expertise. Not that this fact is much discussed.

The low status of 'maintenance engineering' is nothing new. In the 1960's, the British government attempted to rename it 'terotechnology', which derives from the Greek 'teros', meaning 'to watch, observe, guard,…'. Today 'terotechnology' can be described as the maintenance of assets in optimal manner in pursuit of optimizing economic life cycle costs. Flow meter maintenance practices could therefore fall under the term terotechnology.

Whether it is named so or not, terotechnology, including the maintenance of multiple flow meters, is a perpetual issue for many hydrocatbon production and transmission companies. Any tool to help optimize flow meter maintenance efficiency is helpful. Most flow meter verification systems, i.e. 'diagnostic suites', were developed and marketed primarily as warning systems for custody transfer and fiscal mis-measurement. Nevertheless, they are potentially extremely useful for the closely related subject of maintaining flow meters in an optimal manner, i.e. flow meter terotechnology.

However, any such comprehensive flow meter verification system must in practice be automated. Most users do not have the skill set, or the time, or the inclination, to regularly interact with each and every meter's diagnostic software. To be truly useful as an aid to flow meter maintenance teams, these meter verification systems must run unattended. They must be capable of actively sending, or at least passively presenting, detailed information about any abnormalities, without the user actively having to exert significant time and effort to seek this information. And, the more capable the automated meter verification system, the more optimal the maintenance activities should be. It is the development of these verification systems that allows industry to switch from the old method of routine scheduled maintenance (RSM) to the new desired method of condition base maintenance (CBM).

3. STATE OF THE ART OF FLOW METER VERIFICATION SYSTEMS

As no flow meter is infallible there is a drive for modern flow meters to have self-contained internal verification systems. Flow meter verifications systems are arguably the cutting edge of flow meter technology. These verification systems are comprised of multiple individual diagnostic tests derived from various analytical methods applied to the meter instrumentation's primary signals. The combined set of any meter's various diagnostic tests is commonly called the meter's 'diagnostic suite'. Such diagnostic suite verification systems ensure the user that most meter malfunctions will be noticed.

Flow meter users tend to ask three things from the developers of flow meter diagnostic suites. They want to know if 1) it will indicate when something is wrong? If so, 2) will it say what is wrong? And if so, 3) will it tell the operator the associated flow prediction bias? For state of the art flow meter diagnostic suites the answers are:

1) The diagnostic suite needs to have at least one diagnostic test that is sensitive to the specific problem, and the problem will have to be significant enough to cross that diagnostic test's sensitivity threshold. But yes, modern diagnostic suites will indicate a problem exists for most common malfunctions.

2) A modern flow meter diagnostic suite produces multiple individual diagnostic test results. Collating them produces an output diagnostic pattern. Therefore abnormal pattern recognition techniques can be used to match common

malfunctions to particular abnormal diagnostic patterns. However, the state of the art of such pattern recognition tends to be rudimentary. Many flow meter diagnostic results are rather ambiguous. The state of the art of flow meter diagnostic technology is hand crafted (i.e. not artificial intelligence learned) heuristic diagnostic pattern recognition. The DP Diagnostics orifice meter diagnostic system uses such automated pattern recognition to supply a list of possible common malfunctions in order of their probability. Depending on the diagnstic pattern a specific malfunction or a short list of probable malfunctions are offered.

3) Automatically identifying a particular malfunction with any flow meter's diagnostic suite is challenging. Therefore, little to nothing has been done on the follow on task of estimating the associated flow prediction bias for a predicted malfunction type. However, it has now been realised that such a system is possible for the orifice meter verifciation system.

The following development of orifice meter diagnostics was achievable since its conception. The delay has been largely down to preconcieved perceptions. In the early period of development it was seen as valuable enough to achieve a diagnostic system that could show when there was a malfunction, and perhaps from pattern recognition what that malfunction may be. However, as there are practically an infinite amount of types, magnitudes, and combinations of malfunctions it was considered a chrimera, a fools errand, to try and match pattern recognition to specific malfunctions ***and*** associated flow prediction biases. With theoretically infinite possibilities any such system would inherently be incomplete, and hence imperfect. However, such an ivory tower blinkered view misses a crucial point, i.e., *a technology does not need to work perfectly all of the time to be of considerable practical use most of the time*.

Therefore we can do what we always do in life, compromise. Simplifying assumptions can whittle down the number of possibilities to something manageable. In practice, many and probably most flow meter malfunctions are caused by a relatively few common singular problems, and not combinations of complex rare problems. On that point, an orifice meter verification system has now been developed that can 1) identify a specific single malfunction type, or short list a few single malfunction types that can cause specific diagnostic patterns, and then 2) assign corresponding estimated flow prediction biases to each malfunction case.

4 The Nature of Flow Meter Diagnostic Suite Constituent Parts

In order to learn more from flow meter diagnostics it is first necessary to learn more about flow meter diagnostics. Before reviewing and developing the orifice meter diagnostic suite it is first beneficial to consider some fundamental facts regarding the nature of diagnostic tests.

The physicist Lord Kelvin stated: "*When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts advanced to the stage of science*."

That insight has consequences to flow meter diagnostic suites. Flow meter diagnostic results tend to be treated as qualitative subjective information, not quantitative objective information. Nevertheless, in reality most flow meter diagnostic suites contain an assortment of subjective and objective diagnostic tests.

An objective diagnostic check can be defined as where the diagnostic result is derived from comparison with physical law, and not just comparison with intuition, opinion, or some general rule of thumb set by experience. It compares a measureable diagnostic value to a baseline fixed by physical law, thereby creating a *quantitative* objective numerical result. You *"measure what you are speaking about, and express it in numbers, and you know something about it*". It is a clear and precise diagnostic statement. Objective diagnostic tests are useful for both measuring *absolute* changes and monitoring *relative* changes in a system's performance.

A subjective diagnostic check can be defined as where the diagnostic result is not derived from comparison with physical law, but rather comparison with intuition, opinion, or some general rule of thumb set by experience. It compares a measureable diagnostic value to an arbitrary variable baseline. With a changeable / debatable baseline such diagnostic results are not truly expressible by meaningful numbers. The ambiguous nature of this baseline produces a *qualitative* subjective result. Such subjective results are perhaps "the beginning of knowledge", and hence valuable, but all the same, the knowledge is of a more meager kind. It is an ambiguous and imprecise diagnostic statement. Subjective diagnostic tests are therefore really only useful for monitoring *relative* changes in instrument performance.

Hence, objective diagnostic tests tend to be more powerful, i.e. more useful, than subjective diagnostic tests. That is, *not all diagnostic tests are created equal*. Some inherently contain more useful information than others. That is not to say that subjective diagnostic tests do not have their place. They certainly do. A subjective diagnostic test is far better than no diagnostic test, and an objective test coupled with a subjective test is more useful than an objective test alone. The more distinct separate pieces of information a diagnostic suite contains, the more unique the corresponding diagnostic pattern for each malfunction, and the more conducive to successful pattern recognition it is.

However, once a malfunction has been identified by such a diagnostic pattern, in order to make a defensible accurate estimate of the corresponding meter flow prediction bias you *must* use objective diagnostics. With objective diagnostics offering a quantifiable absolute precise measurement, they offer a portal to calculating an associated precise flow prediction bias. Subjective diagnostics offer only relative vague results, and hence there is no way to use them to make precise numerical predictions. Therefore, for a flow meter diagnostic suite to be successfully developed such that it can state flow prediction biases for malfunctions it identifies, it will need to use the *quantitative* objective results produced from objective diagnostics as the tools.

It is important to realize that it is not possible to directly jump from stating a malfunction type to predicting an associated flow prediction bias. There is seldom discussed *vital* middle step. In order to predict the flow prediction bias associated with an identified flow meter malfunction type, it isn't good enough to just identify the *type* of malfunction, you also have to *quantify the magnitude* of that malfunction. This is the essential middle step and it is no trivial matter. In fact, this step is the most difficult in the whole process. After the flow meter diagnostic suite indentifies the type of problem it must then accurately estimate the magnitude of that problem, i.e. express it in a quantifiable / measureable way. Only when the magnitude of the malfunction is expressible in numbers are you in a position to then make quantifiable predictions about its effects.

Finally, before reviewing the existing orifice meter diagnostics system and then developing it, it is necessary to make two further comments regarding the nature of objective diagnostic tests:

First, in practice no diagnostic test is *truly* objective. All measured parameter values include instrumentation reading uncertainties. These instrument uncertainties are by their nature subjective. Hence, in practice even theoretically objective diagnostic tests have an element of subjectivity. Nevertheless, in practice this is not problematic. The influence on the theoretical objective results of the instrument uncertainties is small, and often trivial. There is still clearly two sets of diagnostic tests, i.e. objective tests based on the theory of physical law, and subjective tests that are not.

Secondly, calibrated diagnostic parameter values known to be reproducible from laboratory to the field can be used to practically create objective diagnostic tests. This is the application of a key axiom in science, paraphrased as: '*Whatever is true of everything we've seen here and now is true of everything everywhere in the future*'. If the same flow meter remains effectively physically unchanged, and the installation between the calibration and field application is effectively the same, then the flow meter's performance across the same calibration and field flow conditions should remain unchanged. Such calibration values are therefore valid baselines, and any measured change in performance is therefore, from a practical standpoint, an objective result. But, this is only true of *reproducible* calibration results. Due to inevitable various subtle installation and flow condition differences not all calibrated parameters are reproducible in the field. Only calibration parameters that are truly reproducible, i.e. transferable to the field, can be used for objective diagnostic tests.

Let us now review the orifice meter diagnostic suite before applying these principles to the task of quantifying the magnitude of malfunctions, and thereby estimating the flow meter's associated flow prediction bias.

5. ORIFICE METER DIAGNOSTIC SUITE COMPOSITION REVIEW

Figure 2 shows a simplified sketch of an orifice meter with instrumentation and the pressure field through the meter body. There is an extra (3^{rd}) pressure port 6D downstream of the plate. As shown in Figure 2, this allows the reading of not just the traditional DP (ΔP_t), but also the recovered DP (ΔP_r), and the permanent pressure loss DP (ΔP_{PPL}). Traditional orifice meter installations only read a single 'traditional' DP, ΔP_t. The extra information contained in the pressure field was traditionally ignored. The diagnostic system uses these three DPs to monitor the whole pressure field and extract significantly more information about the flow and meter performance than the traditional orifice meter system.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \qquad \text{-- (1)}$$

Equation 1 (and Figure 2) shows the simplicity of the DP relationships. Any one of these three DPs can be inferred from the other two. The sum of the recovered and PPL DPs gives an inferred traditional ΔP ($\Delta P_{t,inf}$). This inferred traditional $\Delta P_{t,inf}$ should equal the read value. However, there are uncertainties to each DP

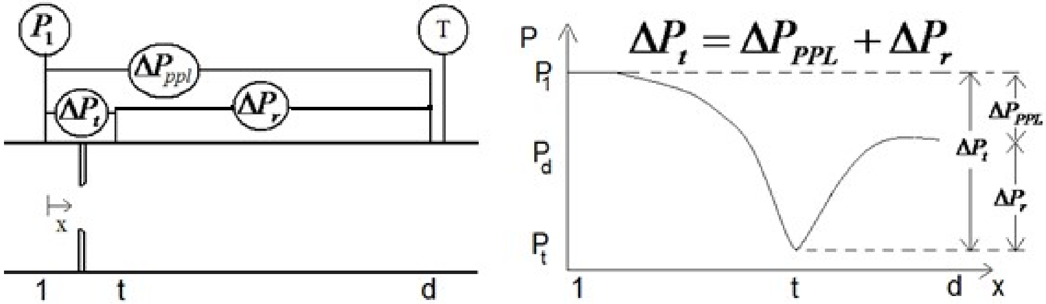

Fig 2. Orifice Meter with Instrumentation and Pressure Field Schematic.

reading, and hence the allowable difference between the inferred and read ΔP_t values is denoted as uncertainty *θ%*. The actual percentage difference is denoted as δ% (see equation 2).

$$\delta\% = ((\Delta P_{t,inf} - \Delta P_t)/\Delta P_t)*100\% \qquad \text{---- (2)}$$

<u>*This is an objective diagnostic test based on a known physical reality, and not just intuition, opinion, or some general rule of thumb set by experience.*</u>

Traditional Flow Equation: $m_t = \frac{A\beta^2}{\sqrt{1-\beta^4}} \varepsilon\, C_d \sqrt{2\rho\Delta P_t}$, uncertainty ± x% --- (3)

Expansion Flow Equation: $m_r = \frac{A\beta^2}{\sqrt{1-\beta^4}} K_r \sqrt{2\rho\Delta P_r}$, uncertainty ± y% --- (4)

PPL Flow Equation: $m_{ppl} = AK_{PPL}\sqrt{2\rho\Delta P_{PPL}}$, uncertainty ±z% --- (5)

Traditionally, there is a single DP meter flow rate calculation based on the traditional ΔP_t reading, i.e. equation 3. However, the additional two ΔPs give two extra flow prediction calculations, i.e. the expansion meter based on the recovered ΔP_t reading (equation 4) and PPL meter based on the ΔP_{PPL} reading (equation 5). Note that m_t, m_r, and m_{PPL} represent the traditional, expansion and PPL mass flow rate equation predictions respectively. The symbols ρ and ε represents the inlet fluid density and gas expansibility. Symbols A and β represent the inlet area and the beta respectively. Beta is a geometric constant for a given orifice meter, and is calculated by equation 6, where A_t, d, and D denote the orifice area, orifice diameter and inlet diameter respectively.

$$\beta = \sqrt{(A_t / A)} = d/D \qquad \text{--- (6)}$$

The terms C_d, K_r, and K_{PPL} represent the discharge coefficient, the expansion coefficient, and the PPL coefficient respectively. Whereas these coefficients can be found by calibration, standard orifice meters tend to not be calibrated. Hence, they have to be derived from the standards. ISO 5167-2 [1] offers the Reader-Harris Gallagher (RHG) discharge coefficient prediction (see equation 7), which is a function of beta and Reynolds number (see equation 8) where μ denotes fluid viscosity:

$$C_d = f(\beta, Re) \qquad \text{--- (7)}$$

$$Re = 4m/\pi\mu D \qquad \text{--- (8)}$$

ISO 5167 also offers a prediction for the Pressure Loss Ratio, 'PLR' (i.e. the ratio $PLR = \Delta P_{PPL}/\Delta P_t$). This ISO equation links the orifice meter PLR to the beta and discharge coefficient, i.e. $PLR = f(\beta, C_d)$. However, this theoretical equation's assumptions become less valid as beta increases, and the discharge coefficient influence is known to be a second order effect. Hence, there are now $PLR = f(\beta)$ data fits to predict the base line PLR:

$$PLR_{base} = f(\beta) \qquad \text{-- (9)}$$

It can then be shown, that the expansion (K_r) and PPL (K_{PPL}) coefficients are derivable without calibration from the ISO C_d and selected PLR predictions, i.e.:

$$K_r = (\varepsilon C_d)/\sqrt{(1-PLR_{base})} \qquad \text{-- (10)}$$

$$K_{PPL} = (\beta^2/\sqrt{(1-\beta^4)}).((\varepsilon C_d)/\sqrt{(PLR_{base})}) \qquad \text{-- (11)}$$

Every orifice meter with a downstream pressure tap is in effect three flow meters. All three flow coefficients are considered reproducible in the field and can be used to produce objective tests. Furthermore, the physical law of conservation of mass dictates that these three mass flow rate predictions should be the same. Hence, the <u>*inter-comparison of any two of the three mass flow rate predictions is an objective diagnostic check*</u>. There are three pairs of flow rate predictions, hence three objective diagnostic tests. Equations 12, 13, and 14 show the respective pair's flow rate comparison. Naturally these mass flow predictions have associated uncertainties induced by DP reading, flow coeffcient prediction uncertainties etc.. Let us introduce these uncertainties as x%, y% & z% for the traditional, expansion, and PPL meters respectively. By convention, a correctly operating meter will have no difference between any two flow equations greater than the root sum square of the two uncertainties. The maximum allowable difference between any two flow rate equations, i.e. $\Phi\%$, $\xi\%$, and $v\%$ is shown in equation set 15 thru 17.

Traditional to PPL Meter Comparison :	$\psi\% = [(m_{PPL} - m_t)/m_t]*100\%$	-- (12)
Traditional to Expansion Meter Comparison:	$\lambda\% = [(m_r - m_t)/m_t]*100\%$	-- (13)
PPL to Expansion Meter Comparison:	$X\% = [(m_r - m_{PPL})/m_{PPL}]*100\%$	-- (14)
Traditional/PPL Meter allowable difference:	$\Phi\%=\sqrt{((x\%^2)+(z\%^2))}$	-- (15)
Traditional/Expansion Meter allowable difference:	$\xi\%=\sqrt{((x\%^2)+(y\%^2))}$	-- (16)
Expansion/PPL Meters allowable difference:	$v\%=\sqrt{((y\%^2)+(z\%^2))}$	-- (17)

Equation 1 can be re-written as equation 1a. Hence, for any given PLR there are corresponding Pressure Recovery Ratio ($PRR=\Delta P_r/\Delta P_t$), and Recovered to PPL DP Ratio ($RPR= \Delta P_r/\Delta P_{PPL}$) values. The PLR, and hence the PRR and RPR, are characteristics of any given DP meter. These DP Ratios can be found by calibration, but as orifice meters are not typically calibrated they can be found by use of the chosen $PLR = f(\beta)$ relationship. That is, derive the correct 'baseline' PLR (PLR_{base}) from equation 9 and then apply equations 18 and 19 to derive the corresponding PRR_{base} and RPR_{base} baselines respectively. These predictions of PLR, PRR, and RPR have assigned uncertainties of a%, b%, and c% respectively.

$$(\Delta P_r/\Delta P_t) + (\Delta P_{PPL}/\Delta P_t) = PLR + PRR = 1 \qquad \text{-- (1a)}$$

$$PRR_{base} = 1 - PLR_{base} \qquad \text{-- (18)}$$

$$RPR_{base} = (1 - PLR_{base}) / PLR_{base} \qquad \text{-- (19)}$$

All three of these DP ratio predictions are based on historical massed orifice meter calibration PLR results, and are considered transferable from the laboratory to the field. Hence, *these DP ratio parameters produce objective diagnostics*. The measurable quantities *α%, γ%, and η%* represent the quantifiable difference between measured and baseline DP ratios (see equations 20 thru 22).

PLR test :	$\alpha\% = [(PLR_{read} - PLR_{base})/PLR_{base}]*100\%$	-- (20)
PRR test:	$\gamma\%=[(PRR_{base} - PRR_{base})/PPRR_{base}]*100\%$	-- (21)
RPR test:	$\eta\% = [(RPR_{base} - RPR_{base})/RPR_{base}]*100\%$	-- (22)

The DP meter diagnostic display is conducive for hand crafted heuristic diagnostic pattern recognition. These seven diagnostic checks can be denoted as four points on a graph.

For the DP_t and DP_{PPL} pair:	$x_1 = \psi\%/\Phi\%$	and	$y_1 = \alpha\%/a\%$
For the DP_t and DP_r pair:	$x_2 = \lambda\%/\xi\%$	and	$y_2 = \gamma\%/b\%$
For the DP_{PPL} and DP_r pair:	$x_3 = X\%/v\%$	and	$y_3 = \eta\%/c\%$
For the DP_t and $DP_{t,inf}$ pair	$x_4 = \delta\%/\theta\%$	and	$y_4 = 0\%$

Table 1 shows the individual objective diagnostic test results within the suite that would or would not create a warning. Each of the seven diagnostic tests has *normalized data*, i.e. each diagnostic parameter percentage difference output is divided by the allowable percentage difference for that parameter.

DP Pair	No Warning	WARNING	No Warning	WARNING
ΔP_t & ΔP_{PPL}	$-1 \le x_1 \le +1$	$-1>x_1$ or $x_1>+1$	$-1 \le y_1 \le +1$	$-1>y_1$ or $y_1>+1$
ΔP_t & ΔP_r	$-1 \le x_2 \le +1$	$-1>x_2$ or $x_2>+1$	$-1 \le y_2 \le +1$	$-1>y_2$ or $y_2>+1$
ΔP_{PPL} & ΔP_r	$-1 \le x_3 \le +1$	$-1>x_3$ or $x_3>+1$	$-1 \le y_3 \le +1$	$-1>y_3$ or $y_3>+1$
$\Delta P_{t,read}$ & $\Delta P_{t,inf}$	$-1 \le x_4 \le +1$	$-1>x_4$ or $x_4>+1$	N/A	N/A

Table 1. The DP Meter Diagnostic Results.

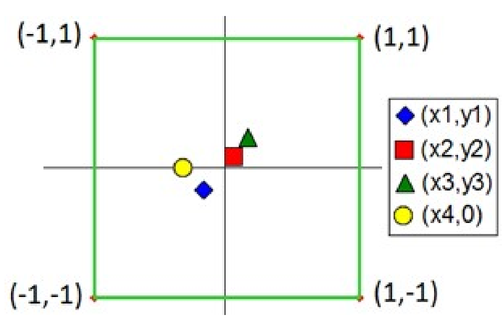

Fig 3. Normalized Diagnostic Box (NDB) Display.

Figure 3 shows the standard DP meter diagnostic suite display. Considering Table 1, with all seven diagnostic coordinates within the normalized diagnostic box ('NDB') no meter malfunction is found. But one or more diagnostic coordinate/s outside of the NDB indicates a warning. Furthermore, when a warning is shown, i.e. one or more point/s are outside the NDB, the position of all four points set by the seven diagnostic coordinates, i.e. the 'diagnostic pattern', gives information to what the source of the problem is.

These seven orifice meter objective quantifiable diagnostic tests could be described as constant parameter 'static' diagnostic tests, meaning the parameters used discount any small statistical dynamic variations and average them out. Such tests tend to be reproducible from calibration laboratory to field, and produce objective quantitative diagnostic tests. However, there are also subjective qualifiable diagnostic tests that could be described as variable parameter 'dynamic' statistical diagnostic tests, meaning the parameters used specifically monitor dynamic variations. Such tests tend not to be reproducible from calibration to field, and produce subjective qualitative diagnostic tests.

There is such a test for orifice meters, i.e. an 8th orifice meter diagnostic test. This test, the exacting analysis of the DP signal and corresponding diagnostic parameter dynamic behaviour, is a dynamic subjective diagnostic test where a variable parameter is monitored. It is described by Rabone et al [2]. In truth, there are multiple analytical techniques for monitoring dynamic behaviours, so it could be argued that there are multiple orifice meter subjective diagnostic tests, but we will consider them all under one umbrella term here.

Fluctuation of primary signals is not easily predictable by physical law, and such calibration data is not generally transferable from calibration laboratory to the field. Small installation peculiarities and the secondary flow conditions, e.g. flow pulsation from compressors, light pipe vibration, slight disturbance from upstream components etc., can vary these parameters in subtle unpredictable ways. Hence, this subjective diagnostic test is useful specifically for trending an in-service meter's instrumentation output over time only. It is not included in the orifice meter output display (Figure 3) but it is accounted for in the background pattern recognition capabilities.

Diagnostic Check	**Diagnostic Type**
PPL to Traditional Mass Flow Comparison (x_1)	objective
Recovered to Traditional Mass Flow Comparison (x_2)	objective
Recovered to PPL Mass Flow Comparison (x_3)	objective
PLR Shift from Calibrated Baseline (y_1)	objective
PRR Shift from Calibrated Baseline (y_2)	objective
RPR Shift from Calibrated Baseline (y_3)	objective
DP Summation Integrity Check(x_4)	objective
DP Reading and DP Ratio Standard Deviation Shifts	subjective

Table 2. Orifice Meter Diagnostic Tests Objective / Subjective Designation.

Table 2 shows the eight orifice meter diagnostic tests. It is the diagnostic pattern produced by these eight tests that is used for pattern recognition. For all there is only a single subjective diagnotsic test in the diagnostic suite it is a very useful addition for pattern recognition. For example, wet gas flow, a blocked impulse line, and errnoeous high orifice diameter keypad entry all produce the same *average* diagnostic pattern. However, this subjective test on the instrumentation dynamic bevaiour separates the erroneous geometry from the other two possibilities. An erroneous geometry use has normal DP signal variation. However, the other two possibilities do not. The subjective diagnostic can then further separates the blocked impulse line and wet gas flow options. Wet gas flow causes short period / low amplitude ΔP fluctuation, while a blocked impulse line causes long period / high amplitude ΔP fluctuation. Figure 4 is a schematic pictorially showing the difference. Hence, the subjective diagnostic family of analytical tests is very useful indeed for pattern recognition.

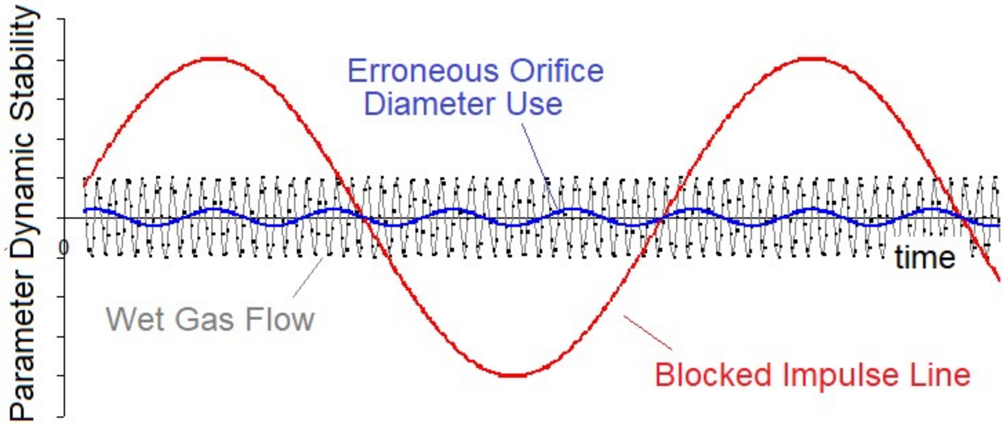

Fig 4. Schematic Pictorial Showing Orifice Meter Parameter Stability (Subjective Diagnostic Test) for Three Different Malfunction Sources.

A flow meter having eight diagnostic checks where seven are objective diagnostic checks is unusual. Other meter designs have more of an objective / subjective mixture in their respective diagnostic suites. As way of an example the Appendix shows such an analysis on the well documented ultrasonic meter diagnostic suite, where out of a total seven tests one is objective, two are arguably objective, and four are subjective. Nevertheless, as Aristotle stated "the whole is greater than the sum of its parts". We will see in Section 7 via worked examples that the sum of these orifice meter objective and subjective diagnostic tests together produce a diagnostic suite where the pattern recognition can identify a specific malfunction, or at least give a short list of a few possible malfunctions.

However, it is now time to discuss how such a system can be developed to not just indicate a problem exists, and suggest what that problem probably is, but also estimate the magnitude of that problem, and therefore what the associated flow prediction bias will therefore.

6. **NEW DEVELOPMENTS**

Presently there are a few limited sporadic academic publications that discuss how select orifice meter malfunctions affect the meters flow prediction. These publications show data on the graduating scale of a specific problem *vs*. the associated induced flow rate prediction bias. Presently, there are only two practical uses for such information.

The first use is to educate the users on the importance of *not* running the meter in this condition, after all, traditionally there is no way of identifying the problem exists, and even now if the present orifice meter diagnostic system is applied to show a problem exists, there is still no method of automatically quantifying it. The second use is related to when either an orifice meter verification system or a routine maintenance check finds a problem. Then, with no present way to automatically quantify the problem with the meter in-situ, the meter has to be taken off line and the malfunction magnitude manually measured, i.e. quantified. *Only then* does this information become available for a flow prediction bias post event analysis desktop exercise. That is, the academic literature on estimating an orifice meter's flow prediction bias is presently only usable after the magnitude of the problem has been quantified from a source external to the meter.

Presently the orifice meter verification system is only used to alert the user to the existence of a problem, and via diagnostic suite pattern recognition to advise what the *type* of problem is. The present system does not and cannot then tell the end user *the magnitude of the problem*. For example, if the *type* of problem is a buckled orifice plate, *how* buckled is the plate? If the *type* of problem is a worn orifice edge, just *how* worn is the edge? Without the ability to quantify the magnitude of the problem the system cannot predict the associated flow prediction bias.

Obviously this is not ideal. Industry would benefit from an orifice meter diagnostic system that could not only indicate what is wrong, *but then also* make an in-situ quantifiable prediction on the magnitude of that specific malfunction, and then estimate the corresponding flow prediction bias. Such a system capable of automatically predicting the magnitude of an identified problem would mean the flow prediction bias could be estimated in real time with the meter in-situ, i.e. without the meter having to come off line for maintenance.

The combination of both objective and subjective diagnostic tests produce a diagnostic suite for which pattern recognition can be applied. For this task subjective diagnostics are valuable and useful. However, when moving on to *quantifying* the magnitude of an identified problem a quantifiable (i.e. objective) diagnostic techniqe *must* be used.

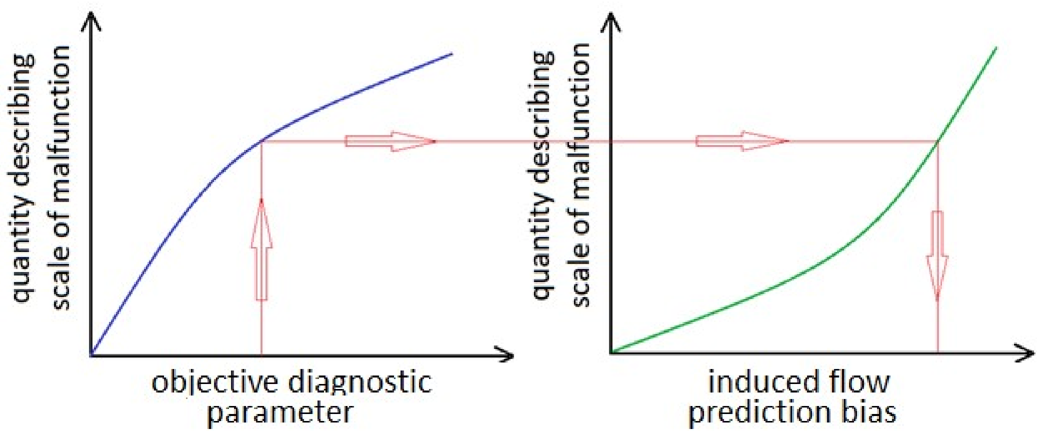

Fig 5. Schematic of Orifice Meter Diagnostic System Malfunction Magnitude and Asociated Flow Prediction Bias Estimtion.

Figure 5 shows how an orifice meter diagnostic suite can estimate a malfunction's magnitude and associated flow prediction bias. For each common malfunction two relationships must be known. Firstly, for each common malfunction, one or more of the quantifiable objective diagnostic test results must be relatable to the magnitude of malfunction (see left hand graph). Secondly, the the magnitude of malfunction must be relatable to the flow prediction bias (see right hand graph). Then the objective test result is related to the flow preiction bias.

DP Diagnostics has long gathered malfunctioning orifice meter data from various laboratories, field tests, and actual service meters. This magnitude of malfunction vs. flow prediction bias can be compared with public data. The quantifiable objective diagnostic test vs. magnitude of malfunction data has never been disclosed. Hence, DP Diagnostics has now developed the system to estimate the magnitude of a malfunction and the corresponding flow prediction bias.

Finally, before considering orifice meter malfunction examples, it is pertinent to remind the reader that: "*A technology does not need to work perfectly all of the time to be of considerable practical use most of the time.*" Orifice meters, like all flow meters, theoretically have a practically infinite amount of types, magnitudes, and combinations of malfunctions. But in general use many, and perhaps most real world malfunctions are caused by one malfunction out of a list of common problems. Hence, on the balance of probabilty it is reasonable to assume that each diagnostic warning from the field is probably caused by one problem only, and not combinations of various different malfunctions.

This issue highlights an important distinction between the primary flow prediction of a meter and it's supplemental diagnostic related capabilities. Flow rate prediction is held to a very high standard, usually quantified as 95% confidence. But diagnostic capabilities are not and need not be held to this high level of confidence to be of significant practical use. For diagnostic techniques, the industry norm tends to be the balance of probabilities, i.e. the preponderance of evidence, choosing the possibility that is more probable than the other.

It is true that a meter could be inflicted with multiple malfunctions. For example, it is feasible that an orifice meter diagnostic pattern could be caused by a combination of a worn edge plate, a buckled plate, a cotaminated meter run, and the geometry keypd entered incorrectly. The effects of each issue play off each other to produce that pattern. But in the majority of cases the simplest solution is *probably* correct, i.e. it's just one problem. This system works on the balance of probabilities, and the most probable cause for any diagnostic pattern is a singular source malfunction. There is an element of 'Occam's Razor' to this. If you don't need to add complexity to explain the result then don't. The simplist explanation is usually correct. And taking this position makes estimating the orifice meter flow prediction bias a realistic aim.

However, considering the number of different common malfunctions, and the wide range of magnitude for each of these malfunctions, the data sets available are very small indeed to achieve this aim. Nevertheless, an oversimplified data fit that you have enough data to create is certainly better than a perfect one that you don't. And the resulting data fits seem to do a good enough job in many cases to make good flow predcition bias estimates.

When described in generic terms these concepts above may seem abstract. However, in practice, once the concept is realized, and considerable effort is complete regarding the mundane but effort intensive gathering and organizing of 1) pattern recognition data, 2) objective diagnostic parameters vs. magnitude of malfunction data, and 3) individual magnitude of malfunction vs. flow prediction bias data, the process is remarkably straight forward. The following worked examples help explain the concept, and the surprising simplicity of the method.

7. Worked Examples

7.1 Erroneous DP Readings

Diagnostic data was logged from a serviceable 10", 0.46β, orifice meter (see Fig 6). The resulting diagnostic display showing correct meter performance is shown on the left side of Figure 7. In order to test the system the meter user introduced a slight leak in the DP transmitter's 5 way manifold. The right hand side of Figure 7 shows the diagnostic pattern result when the traditional DP was

Fig 6. 10”, 0.46β Orifice Meter with an Installed Diagnostic System.

thereby mis-read. Traditionally a problem with the DP reading/s would go un-noticed, but the diagnostic suite now indicates a problem, and specifically indicates an erroneous traditional DP reading as the malfunction source.

The resulting read DPs were ΔP_t=61.1”WC, ΔP_r=14.6”WC, ΔP_{PPL}=50.0”WC, i.e. $\Delta P_{t,inf}$ =64.6”WC. The difference between the read and inferred traditional DP is 5.7%. For the DP reading uncertainty setting of θ = 1% the DP meter diagnostic suite (x_4, y_4) of (5.76,0) correctly shows a DP reading issue.

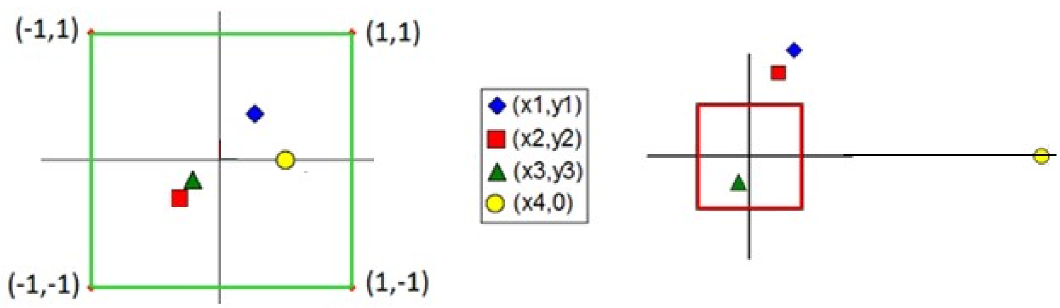

Fig 7. Correct Meter Operation (Left) and Erroneous ΔP_t Reading (Right).

Furthermore, the other six objective diagnostic checks react in a specific way. The points (x_1, y_1) and (x_2, y_2) both move outside the NDB while the other point (x_3, y_3) remains inside the NDB. The pattern indicates specifically what is wrong. The x_4 check is the objective DP integrity check and it confirms an erroneous DP reading. Point (x_3, y_3) used the recovered and PPL DPs and it shows no problem. Points (x_1, y_1) and (x_2, y_2) both show a problem and both use the traditional DP transmitter. Hence pattern recognition shows 1) something is wrong, and then 2) it is specifically a DP transmitter problem, and 3) it is specifically the traditional DP reading that is erroneous.

Select objective diagnostic x_4 which is based on the physical relationship of the three DPs as described by equation 1. The diagnostic pattern showed that ΔP_r and ΔP_{PPL} are trustworthy. Hence this objective diagnostic gives the inferred $\Delta P_{t,inf}$ = 64.6”WC which we can compare to the directly read (and known to be erroneous) ΔP_t=61.1"WC. Thus, the objective diagnostic test tells us that the direct ΔP_t reading has a quantifiable -5.4% bias. Equation 23 shows the associated gas flow prediction bias (*p%*) calculation, shown to be -2.7% by equation 23a. Figure 8 shows the relationship between the objective diagnostic 'x_4' vs. Malfunction Quantity vs. Flow Prediction Bias.

$$p\% = \left\{ \frac{m_{t,biased} - m_{t,correct}}{m_{t,correct}} \right\} * 100\% \approx \left\{ \sqrt{\frac{\Delta P_{t,read}}{\Delta P_{t,\inf}}} - 1 \right\} * 100\% \quad \text{-- (23)}$$

$$p\% \approx \left\{ \sqrt{\frac{61.08}{64.56}} - 1 \right\} * 100\% = -2.7\% \quad \text{-- (23a)}$$

Alternatively, as the diagnostic pattern recognition has identified ΔP_r and ΔP_{PPL} as correctly read, the correct mass flow rates can be predicted by equations 4 and 5 respectively. This can be compared to the meter's erroneous flow rate output to derive the bias ≈ -2.7%.

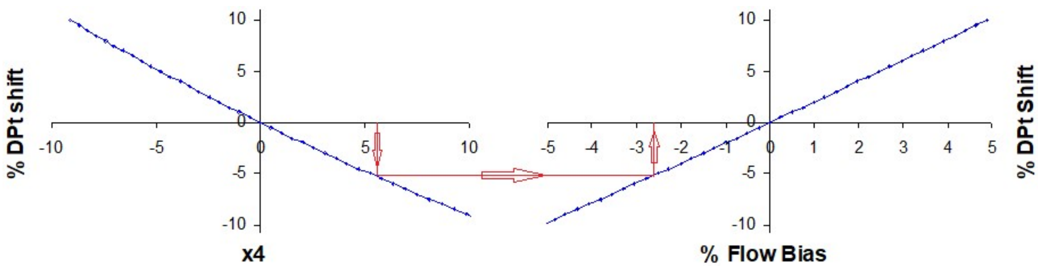

Fig 8. Meter Objective Diagnostic vs. ΔP_t Reading Bias vs. Flow Prediction Bias.

In this DP reading error example the problem is caused by a leaking valve on the DP transmitter manifold. However, the same principle holds for any source of DP reading error, e.g. when a DP transmitter is over-ranged (i.e. 'saturated'), drifting, wrongly calibrated, etc.

7.2 Erroneous Inlet Diameter Entry

A potential problem with orifice meters is keypad entry inlet diameter errors. Traditionally this went un-noticed, but the use of the oifice meter diagnostic suite can now warn of a problem, and offers a short list of possible causes that includes 'erroneous inlet diameter'.

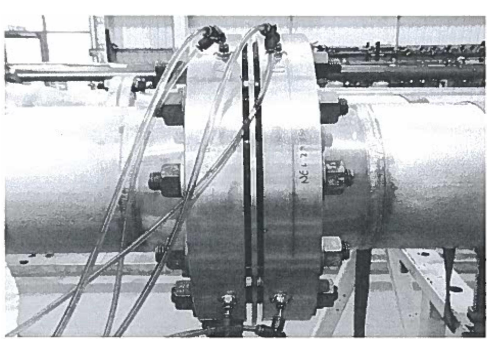

Fig 9. 4", 0.6β Orifice Meter

A 4", sch 40, 0.6*β* paddle plate orifice meter was tested at a water flow facility (see Figure 9). The inlet diameter was 4.026", and the orifice bore was 2.416". The flow conditions were a mass flow of 19.42 kg/s, a Reynolds number of 520,620, and traditional, recovered, and PPL DPs of 51.54kPa, 18.75kPa and 32.74kPa respectively. This produced a read PLR of 0.6363, an ISO C_d prediction of 0.607, and a PLR baseline prediction of 0.6355. The flow prediction and reference agreed to < 0.5%, i.e. the meter is serviceable.

Figure 10 shows the diagnostic suite's response for use of the correct geometry (left side graph) and for use of an arbitrary chosen erroneous inlet diameter of 3.79" (right side graph). The left hand graph shows the meter is operating correctly. The right hand graph shows a pattern that is indicative of a few possible malfunction sources, and excludes all other common malfunction sources. The DP integrity check x_4 shows the DP readings are trustworthy. An erroneous low inlet diameter entry is on the short list of malfunctions that can produce this result.

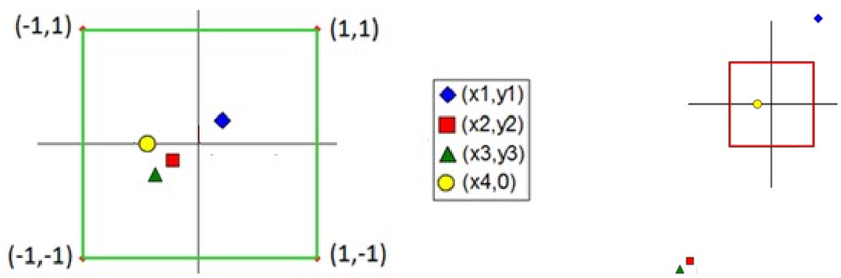

Fig 10. Correct Meter Operation (Left) and Low Inlet Diameter Entry (Right).

The keypad entered geometry suggests the β = d/D = 2.416" / 3.79" = 0.637. Select objective diagnostic y_1 (or more specifically *α%*). This is based on the PLR objective check. The real β value (and not the erroneous β) dictates the actual PLR. As diagnostic x_4 confirms the DPs are read correctly, from equation 9 it is known that $\beta = f(PLR_{read})$. The PLR equation 9a predicts the actual beta via the read PLR of 0.6363.

$$PLR = f(\beta) \quad \text{-- (9)}$$

$$\beta = d/D = f(PLR_{read}) = f(0.6363) = 0.6004 \quad \text{-- (9a)}$$

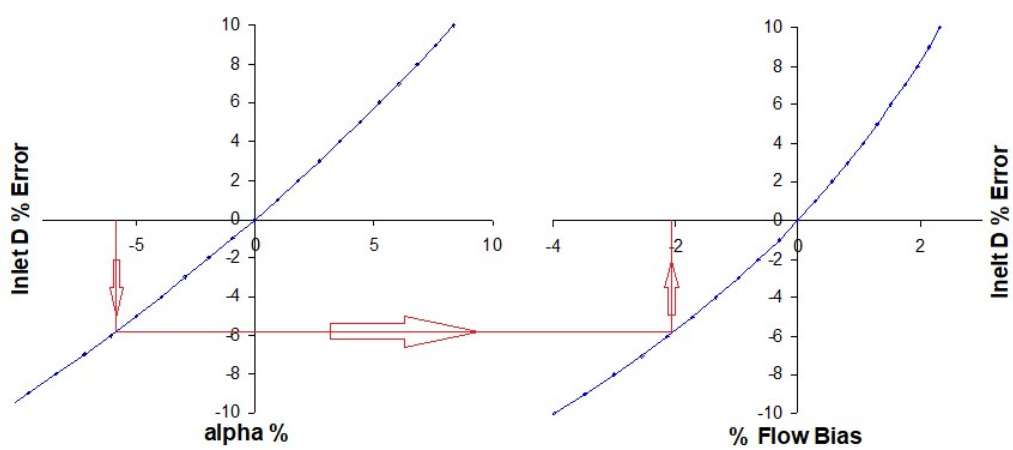

Fig 11. Objective Diagnostic vs. Inlet Diameter Error vs. Flow Prediction Bias.

The objective diagnostic y_1 (i.e. PLR based analysis) has been used to predicted the beta to be 0.6004. The inlet diameter is therefore predicted as D=d/β=2.416"*0.6004 = 4.024". The magnitude of the inlet diameter error is predicted as ((3.79-4.024)/4.024)*100%= -5.8%. The bias on the flow prediction can now be directly calculated, see equation 24.

The erroneous inlet diameter D_{biased} =3.79" produced β_{biased} =0.637, and this method gives a predicted geometry of D =4.024" and β = 0.6004. In this worked example for simplicity it is reasonably assumed that $(\varepsilon C_d)_{biased} \approx \varepsilon C_d$, however in practice a flow computer software would also calculate this second order effect. Equation 24 therefore estimates the flow prediction bias ($p\%$) induced by the erroneous inlet diameter is ≈ -2.1%.

$$p\% = \left\{ \frac{m_{t,biased} - m_{t,correct}}{m_{t,correct}} \right\} * 100\% \approx \left\{ \left(\frac{D_{biased}\,\beta_{biased}}{D\beta} \right)^2 \sqrt{\frac{1-\beta_{biased}^4}{1-\beta^4}} - 1 \right\} * 100\% \quad \text{--(24)}$$

Figure 11 shows the objective diagnostic parameter $a\%$, i.e. the un-normalised y_1 value, being used to predict the magnitude of the problem, i.e. the percentage bias in the inlet diameter, and from there the associated percentage flow prediction bias.

7.3 Erroneous Orifice Diameter Entry

The orifice diameter value could be erroneous entered into the flow calculation. Or during maintenance, a new orifice plate of different orifice diameter to the preceeding plate was installed, but the flow computer calulation was not updated. Traditionally this erroneous orifice diameter value went un-noticed, but the use of diagnostic suite now warns of a problem, and offers a short list of possible causes that includes 'erroneous orifice diameter'.

For the same data set as discussed in example 7.2 (while using the correct inlet diameter) consider the case where the true orifice diameter of 2.416" was erroneously entered as 2.**5**16". Figure 12 shows the diagnostic suite's response for use of the correct geometry (left side) and for use of the erroneous orifice diameter (right side). The left hand graph shows the meter is operating correctly. The right hand graph shows a pattern that is indicative of a few possible malfunction sources, and excludes all other common malfunction sources. The DP integrity check x_4 shows the DP readings are trustworthy. An erroneous high orifice diameter entry is one of the few possible sources that can produce this diagnostic pattern.

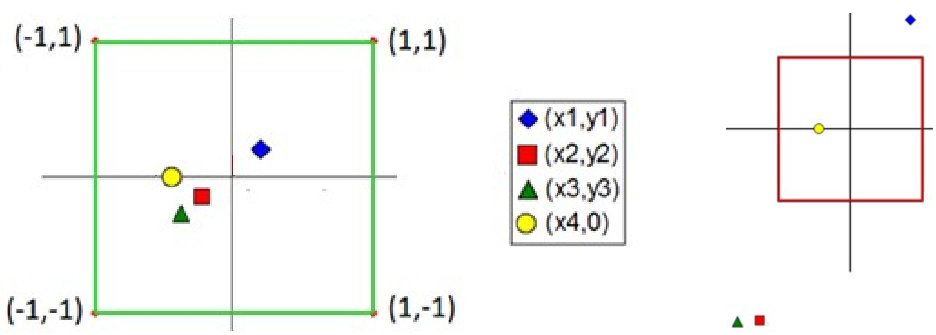

Fig 12. Correct Meter Operation (Left) and High Orifice Diameter Entry (Right).

The keypad entered geometry suggests β=d/D=2.516"/4.026"=0.625. Again select objective diagnostic $a\%$ and predict the actual beta from the read PLR. As the DP integrity check x_4 indicates the DPs are correct we can trust the read PLR, and this again predicts the beta via equation 9 as 0.6004. Hence, the actual inlet diameter is estimated as: $d=D*\beta$=4.026"*0.6004 =2.417". The magnitude of the orifice diameter error is predicted as ((2.516-2.417)/2.417)*100%=+4.1%.

The erroneous orifice diameter induced flow prediction bias (*p%*) can now be directly calculated, see equation 25. The erroneous beta is β_{biased} =0.625, and the predicted beta is β_{biased} =0.6004. Again, in this worked example for simplicity it is reasonably assumed that $(\varepsilon C_d)_{biased} \approx \varepsilon C_d$, however in practice a flow computer software would also calculate the second order effect. Equation 25 therefore estimates the flow prediction bias (*p%*) induced by the erroneous inlet diameter is ≈+9.8%. Figure 13 shows the objective diagnostic parameter *a%* being used to predict the magnitude of the source of the problem (i.e. the percentage bias in the orifice diameter) and from there the associated percentage flow prediction bias.

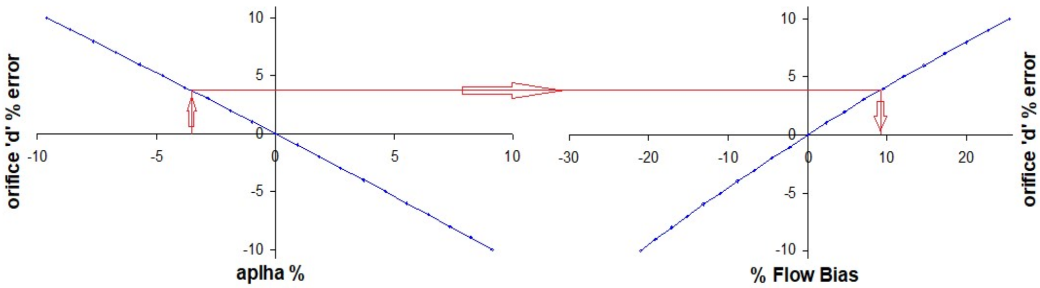

Fig 13. Objective Diagnostic vs. Orifice 'd' Error vs. Flow Prediction Bias.

$$p\% = \left\{ \frac{m_{t,biased} - m_{t,correct}}{m_{t,correct}} \right\} * 100\% \approx \left\{ \left(\frac{\beta_{biased}}{\beta} \right)^2 \sqrt{\frac{1-\beta^4}{1-\beta_{biased}^4}} - 1 \right\} * 100\% \quad \text{-- (25)}$$

7.4 Worn Orifice Edge

An orifice plate should have a sharp perpendicular edge. Worn orifice plates cause the meter to have a negative flow prediction bias. Traditionally this went un-noticed, but use of diagnostic suite now warns of a problem, and offers a short list of possible causes that includes 'worn edge'.

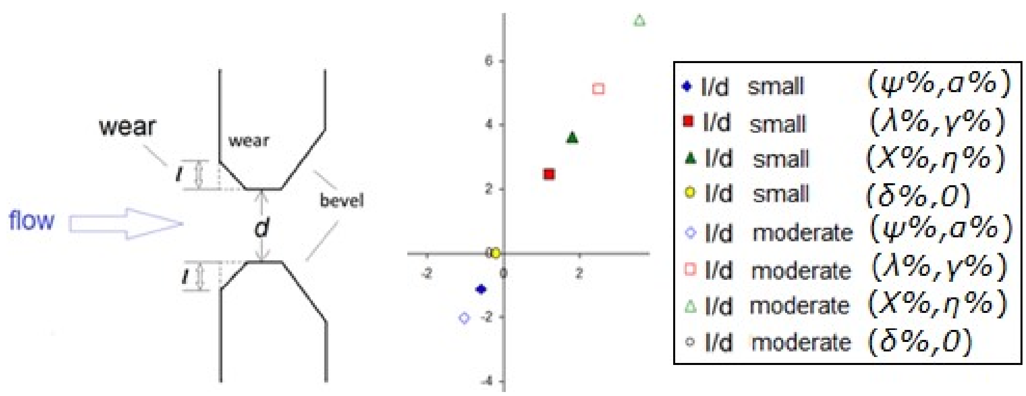

Fig 14. Modelling Orifice Plate Edge and Sample DP Meter Diagnostic Suite Data.

A problem when discussing wear on an orifice plate is what quantifying parameter should be used? Wear is never the same on any two plates. However, modeling the wear as a symmetrical chamfer with height / depth 'l', i.e. as a wear height (l) to orifice diameter 'd', (*l/d* ratio), see Figure 14, gives reasonable predictive results. The small 3rd party public data set on the issue models wear as a smooth circular segment of radius 'r', i.e. (*r/d* ratio). Both models are approximate and in practice with r ≈ l they are effectively equivalent.

Over several years DP Diagnostics tested plates in the laboratory and in the field with varying degrees of worn edge, e.g. see Figures 15 and 16. DP Diagnostics recorded the worn edge (*l/d*) vs. objective diagnostic values vs. flow prediction bias (*p%*) data. Figure 14 shows the description of the edge wear and sample un-normalised diagnostic data.

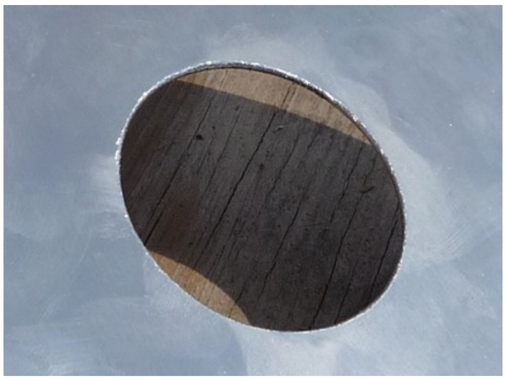

Fig 15. Filed orifice edge.

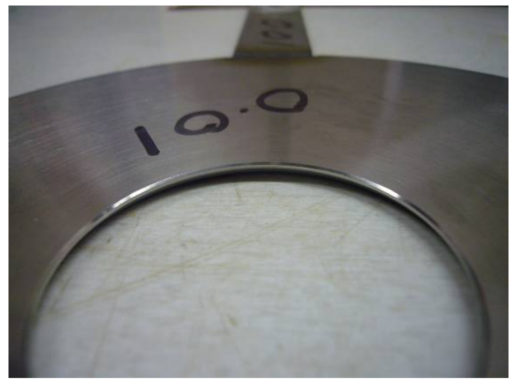

Fig 16. Chamfered orifice edge.

Figure 14 show the un-normalized objective diagnostic results (*ψ%,a%*), (*λ%,γ%*), (*X%,η%*), and (*δ%,0*). Whereas the DP reading integrity check (*δ%*) has no relationship with the edge wear, and nor should it, the other six objective diagnostic parameters do. In this case the RPR objective diagnostic check is the most sensitive, i.e. $\eta_{\%}$ *vs. l/d* value (although the any of the six could be successfully used).

Figure 17 shows orifice edge wear (*l/d*) vs. measured objective diagnostic *η%* data, with a data fit, i.e. $l/d=f(\eta_{\%})$. The last step of estimating the flow prediction bias (*p%*) for that edge wear estimation (i.e. *l/d*) is through the published equations stating *p%=f(l/d)*.

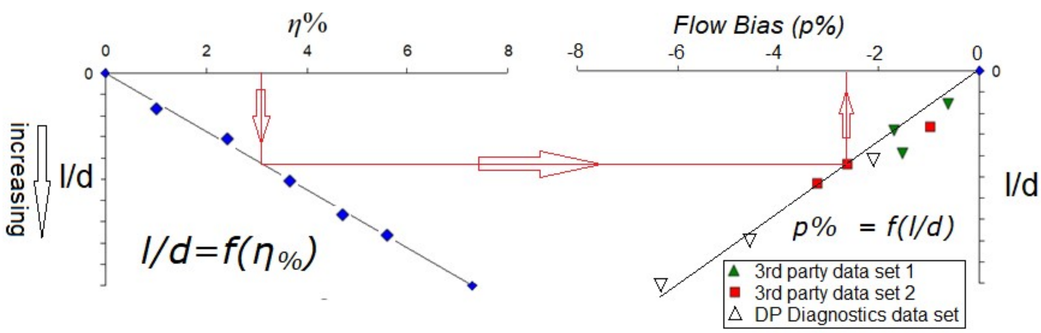

Fig 17. Objective Diagnostic vs. Amount of Edge Wear vs. Flow Prediction Bias.

Figure 17 shows the similarity of DP Diagnostics data to the 3rd party data published by Reader-Harris [4]. Figure 18 reproduces this 3rd party data. The 3rd party data was originally plotted as *r/d* vs. shift in meter C_d. This data was said to have a gradient of 550. However, this is an academic frame of reference. In practice end users do not change the C_d as a problem develops, but rather unwittingly keep the C_d constant and (without a diagnostic suite) unknowingly suffer a bias. Therefore, this data is plotted in Figure 18 in the more practically useful form as *r/d* (or *l/d*) vs. flow prediction bias (*p%*). This then produces a 3rd party data set gradient of approximately -550. The DP Diagnostics data set, for which a sample is shown extending to greater amounts of wear, independently shows a gradient of gradient of -552, a remarkably similar result.

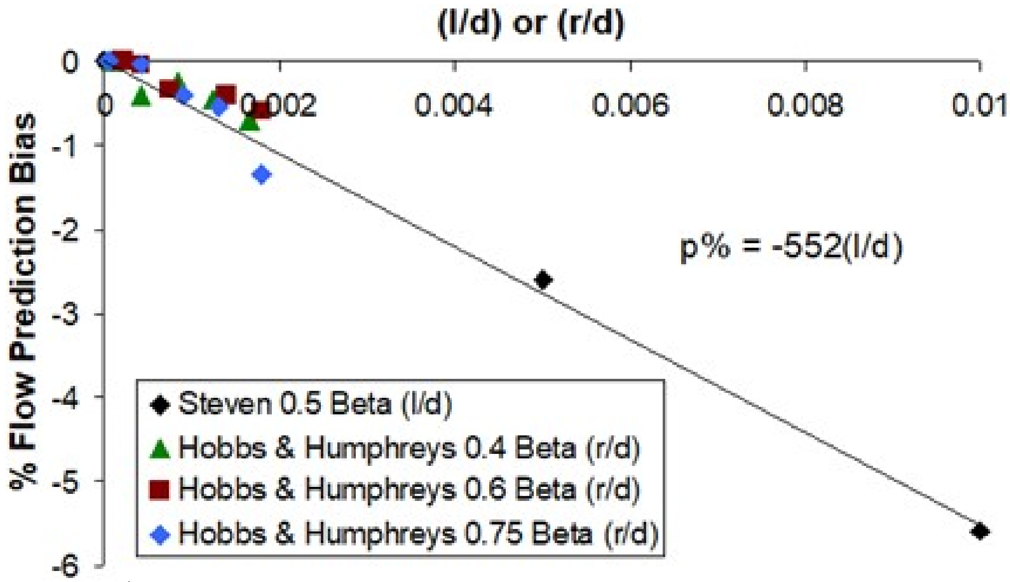

Fig 18. 3rd Party and DP Diagnostics Edge Wear vs. %Flow Prediction Bias (p%).

Traditionally the existence of the edge wear and associated flow prediction bias is unknown. Traditionally, such wear is only found once the meter is taken off-line for routine scheduled maintenance, and the magnitde of the wear then manually measured. Only once the wear is mannually measured can the associated flow prediction bias can be estimated. However, this information (e.g. see Figure 18) is of very limited practical use. Without knowing when the wear occurred, or over what time frame the wear and associated flow prediction bias developed, there is no defensible way to apply this information to a corrective back calculation of flow rate prediction. The information is far more academic than practical. However, with the use of these diagnostics whilst the meter remains on-line, a problem is noted, a worn edge is stated as one of a few possibilities, any trending in such wear can be actively monitored, and all that time, in real time, the system estimates the magnitude of the wear and the associated flow prediction bias.

7.5 Backwards / Reversed Orifice Plate

Many orifice plate designs have a bevel on the back face (e.g. see Figures 19). Hence, orifice plates are not symmetrical. A common operational mistake is to install the orifice plate backwards such that the bevel instead of the perpendicular edge is presented to the oncoming flow. This induces a significant negative flow prediction bias. Traditionally this went un-noticed, but the use of the diagnostic suite can warn of a problem, and 'backwards plate' is stated as the most probable reason for that particular diagnostic pattern.

The change from a correctly installed plate to a backwards plate is a change from one precise geometry to another. That is, for a specific beta a backward plate always produces the same predictable step shift in all six diagnostic parameters (the seventh x_4 being unaffected). With the DP integrity check (x_4) giving assurance the DPs are read correctly, the reproducible tell-tale six objective diagnostic test results, i.e. specific values for $\psi\%$, $\alpha\%$, $\lambda\%$, $\gamma\%$, $X\%$, and $\eta\%$,

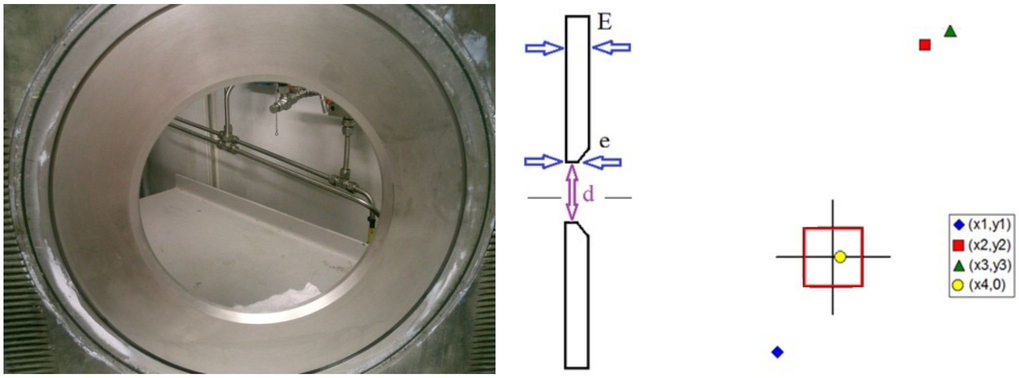

Figure 19. Photograph of Back of Plate, and Sketch of Plate and Diagnostic Suite Reversed Plate Pattern.

directly imply a 'backwards plate'. These precise objective diagnostic test results, indicative specifically of a backward plate, by default also indicate the precise quantity of the magnitude of the malfunction – i.e. the correspeonding precise (*l/d*) shift due to the geometry of the bevel. Then, whilst the meter is still on-line, the associated flow prediction bias (*p%*) can be estimated.

There are various published calculation routines that estimate the flow prediction bias indced by a backwards plate. Reader-Harris [4] gives equations 26 and 27. The plate thickness (*E*) and bevel thickness (*e*) are required, but these are set geometries of the plate used and should therefore be available information in practice.

Researcher Witte suggests for e/E > 0.5 use:

$$p\% = -18.93 + 12.91\beta - 34.04\frac{E}{D} - 8.9\frac{e}{E} + 13.64\left(\frac{e}{E}\right)^2 \qquad \text{-- (26)}$$

Researcher Reader-Harris suggests for e/E ≤ 0.5 use:

$$p\% = -\left(17.2 - 10.4\beta^{2.5}\right)\left(1 - \exp\left(\frac{-1270\frac{(E-e)}{d}}{17.2 - 10.4\beta^{2.5}}\right)\right) \qquad \text{-- (27)}$$

Again, traditionally the backwards installation of the plate and the associated flow prediction bias is unknown. Traditionally, the problem is only found once the meter is taken off-line for routine scheduled maintenance. However, with the use of this diagnostic system whilst the meter remains on-line, a problem is immediately noted, the specific problem is suggested, and all that time, in real time, the system estimates the magnitude of the associated flow prediction bias.

7.6 Buckled / Warped / Bent Orifice Plates

An orifice plate should be perpendicular to the flow. Buckled (i.e. 'warped' / 'bent') orifice plates cause the meter to have a negative flow prediction bias. Traditionally this went un-noticed, but the use of the diagnostic suite can now warn of a problem, and offers a short list of possible causes that includes 'buckled plate'.

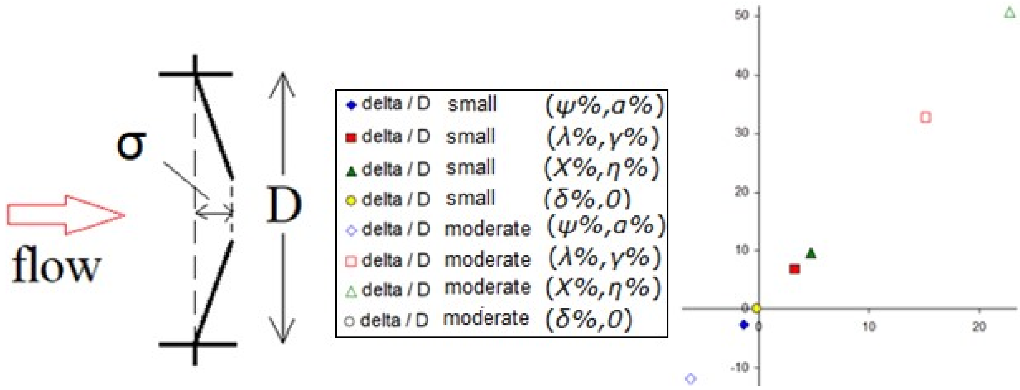

Figure 20. Sketch of Buckled Plate and Diagnostic Suite Buckled Plate Pattern.

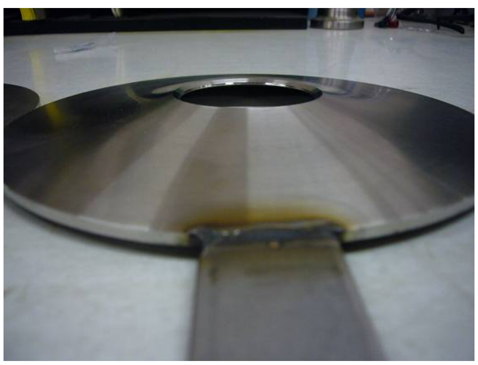

Fig 21. Moderately Buckled Plate.

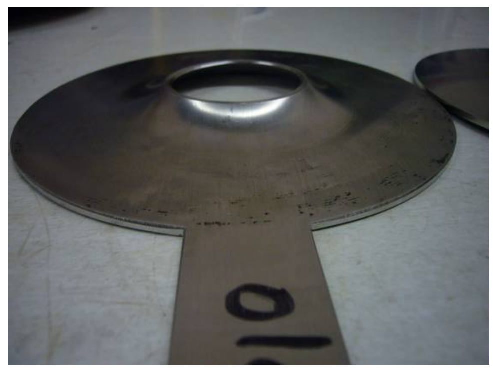

Fig 22. Severely Buckled Plate.

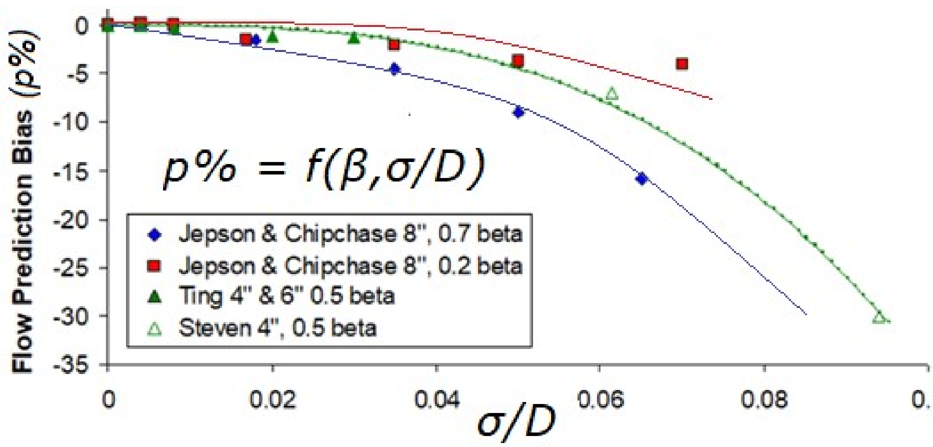

Fig 23. Buckle Magnitude vs. Flow Prediction Bias Data.

When discussing orifice plate buckling it is necessary to chose a parameter to quantify the magnitude of the buckle. Let us modle the buckle as a symmetrical buckle of depth 'σ' to meter inlet diameter 'D', (i.e. a σ/D ratio), see Figure 20.

Over several years DP Diagnostics tested buckled plates in laboratories with varying degrees of buckle, e.g. see Figures 21 and 22. This buckled plate magnitude (σ/D) vs. flow prediction bias ($p\%$) data is similar to the limited 3rd party data sets (see sample data in Figure 23). The buckle (σ/D) vs. flow prediction bias ($p\%$) relationship is somewhat beta dependent, but nevertheless it is possible to estimate the flow prediction bias for a known beta (β) and known magnitude of buckle (*σ/D*). DP Diagnostics recorded the buckle (*σ/D*) vs. objective diagnostic values vs. flow prediction bias (*p%*) data.

Figure 20 show the un-normalized objective diagnostic results (*ψ%,α%*), (*λ%,γ%*), (*Χ%,η%*), and (*δ%,0*). Whereas the DP reading integrity check (*δ%*) has no relationship with plate buckle, and nor should it, the other six objective diagnostic parameters do. In this case the RPR objective diagnostic check is the most sensitive, i.e. $\eta_{\%}$ *vs*. *σ/D* value (although the any of the six could be successfully used). Figure 24 shows, for a fixed beta, orifice plate buckle magnitude (*σ/D*) vs. measured objective diagnostic *η%* data, with a data fit, i.e. $\sigma/D = f(\beta,\eta_{\%})$. The last step of estimating the flow prediction bias (*p%*) for that magnitude of buckling estimation (i.e. *σ/D*) is through the DP Diagnostics data fit *p%=f(β,σ/D)*.

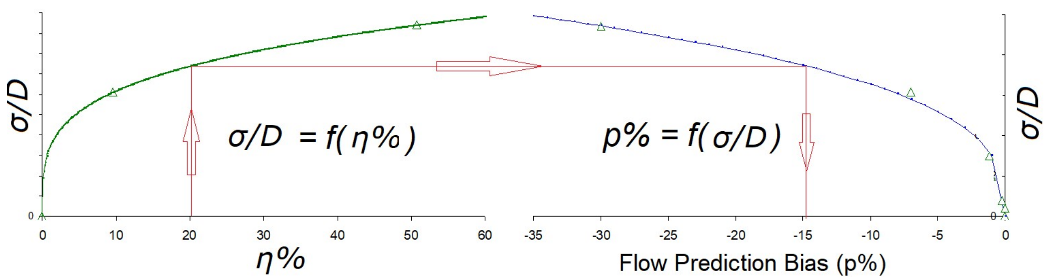

Fig 24. For Fixed β, Objective Diagnostic Parameter (*η%*) *vs.* Buckled Plate (*σ/D*) vs. Flow Prediction Bias (*p%)*.

Traditionally the existence of a buckled plate and the associated flow prediction bias is unknown. Traditionally, the buckle is only found once the meter is taken off-line for routine scheduled maintenance, and the magnitde of the buckle then manually measured. Only once the buckle is manually measured can the associated flow prediction bias can be estimated. However, on its own this information (e.g. see Figure 23) is of very limited practical use. Without knowing when the buckling occurred there is no defensible way to apply this information to a corrective back calculation of flow rate prediction. The information is far more academic than practical. However, with the use of this diagnostic system whilst the meter remains on-line, a problem is noted, a buckled plate is stated as one of a few possibilities, and all that time, in real time, the system estimates the magnitude of the buckle and the associated flow prediction bias.

7.7 Wet Gas Flow

Gas production flows are usually assumed to be dry gas flows. However, in reality upstream gas production flows are often wet gas flows. Even gas transmission lines occassionally have temporary liquid drop out (i.e. condensing water and or heavier hydrocarbons) with local changes in the thermodynamic conditions.

Liquid entrainment with the gas flow (i.e. 'wet gas flow') causes orifice meters to have a positive flow prediction bias. Traditionally this often went un-noticed. However, the use of the diagnostic suite can now warn of a problem, and specifically identify wet gas flow as the source of that problem.

Figure 25 shows an 8", 0.72β orifice meter tested at CEESI for Precision Flow and DP Diagnostics. Figure 26 shows a photograph from the CEESI wet gas flow test

Fig 25. 8”, 0.72β Orifice Meter

viewing port. Figure 27 shows a sample orifice meter diagnostic system display reaction to wet gas flow. As the gas gets wetter (x_1,y_1) moves further into the 1st quadrant, while (x_2,y_2) and (x_3,y_3) both move further into the 3rd quadrant. The DP integrity check $(x_4,0)$ is unaffected by the wet gas flow. This diagnostic pattern created by these seven objective diagnostics is communal to a short listed group of orifice meter problems. However, when the 8th diagnostic test is included, i.e. the subjective test comprising the

Fig 26. Wet Gas Flow in a Pipeline.

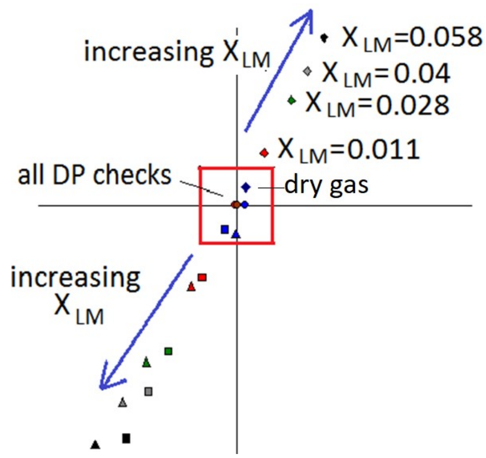

Fig 27. Wet Gas Flow Diagnostic Pattern.

statistical analysis of the primary signals and the associated diagnostic parameters, the wet gas pattern becomes unique and wet gas is specifically identified.

Industry has carried out extensive research into an orifice meter’s reacion to wet gas flow, e.g. Steven [5] and ISO TR 11583 [6] have published a wet gas correction factor of the form $p\% = f(X_{LM}, DR, Fr_g)$. Figure 28 shows the ISO data set. The liquid loading of a wet gas flow can be quantified by the non-dimensional Lockhart Martinelli parameter (X_{LM}). Here ‘*DR*’ denotes the gas to liquid density ratio, and ‘Fr_g’ denotes the gas densiometric Froude number, i.e. non-dimensional pressure and gas flow rate parameters respectively.

The Achilles heel of this ISO orifice meter wet gas flow bias prediction is the user needs to know *how* wet the flow is before the associated gas flow prediction bias (*p%*) can be calculated. Note, the orifice meter wet gas positive prediction bias *p%* is often called the ‘over-reading’ ($OR\% \equiv p\%$). This is exactly analogous to all other orifice meter malfunction flow rate bias predictions. In order to predict the flow prediction bias you first have to quantify the magnitude of the problem, in this case the liquid loading, i.e. the Lockhart Martinelli parameter (X_{LM}).

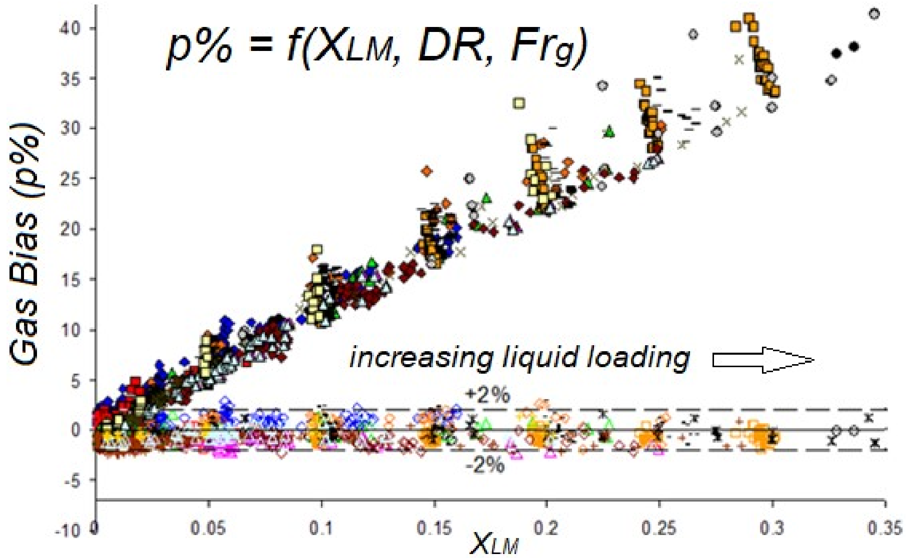

Fig 28. ISO Wet Gas Orifice Meter Data Set.

Using a publicly released limited CEESI Joint Industry Project wet gas orifice meter data set this author discussed this specific issue in 2007 (Steven [7]). This limited data set became the foundation of the Reader-Harris ISO TR 11583 $X_{LM} = f(\beta, DR, PLR)$ data fit. That is, here ISO are taking the objective diagnostic parameter PLR's quantifiable shift from the dry gas baseline value and linking it with a quantitifiable liquid loading (X_{LM}) value. This X_{LM} prediction can then be used in the ISO TR 11583's $p\%=f(X_{LM}, DR, Fr_g)$ equation. The solution is actually an iteration, but regardless, the liquid loading (X_{LM}) and gas flow prediction bias ($p\%$) are calculated.

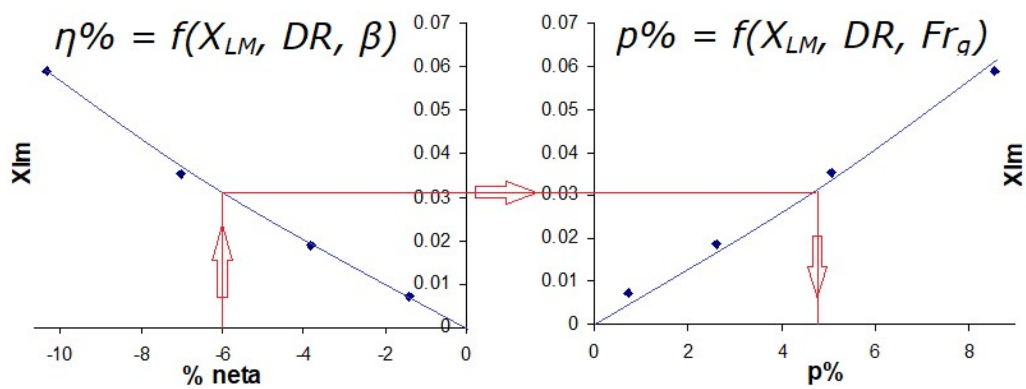

Fig 29. 8", 0.72β, DR 0.058, Fr_g 1.2, Gas / Oil, Orifice Meter Wet Gas Data: Objective Diagnostic Parameter *(η%)* vs. Wet Gas Liquid Loading (X_{LM}) vs. Gas Flow Prediction Bias ($p\%$).

A problem with ISO TR 11583's $X_{LM} = f(\beta, DR, PLR)$ equation is it is rather limited in range. Steven [5] discusses this in some detail. Steven [5] also shows that all six objective diagnostic parameters *ψ%, α%, λ%, γ%, X%,* and *η%* are sensitive to X_{LM}. In fact, *η%* (i.e. the RPR objective diagnostic parameter) is more sensitive than *α%* (i.e. the PLR objective diagnostic parameter being used by ISO). Hence, Fig 29 shows an example of using *η%* (i.e. RPR) to predict the liquid loading instead of *α%* (i.e. PLR). Steven [5] discusses comprehensive data fits linking these objective diagnostic parameters to X_{LM}, e.g. $X_{LM} = f(\beta, DR, PLR)$.

Traditionally the existence of wet gas flow and the associated flow prediction bias is unknown. Traditionally, the presence of wet gas flow is found by accident or by dedicated means external to the meter. Even if the meter user is aware the gas flow is wet a quantified liquid loading is required to calculate the corresponding gas flow prediction bias. However, with the use of this diagnostic system a problem is noted, wet gas flow is specifically identified, trending of the liquid loading is available, and the liquid loading quantity and associated gas flow prediction bias can be estimated all that time, in real time.

8. FURTHER DEVELOPMENTS

There are various different malfunction sources that afflict any given flow meter design. Some are communal to most flow meter designs, e.g. wet gas, inlet flow disturbance, erosion, contamination, instrument faults etc.. Others are specific to that meter design, e.g. for an orifice meter an orifice edge wear, buckled plate, backward plate etc. Some malfunction / problem sources are significantly simpler to quantify than others. A general rule is the less specific the malfunction term, the more challanging it is to quantify.

For example, 'orifice edge wear' is specific. It distinctly describes the change in shape of the square edge. A 'buckled plate' is specific. It distinctly describes the bowing of the plate. But, for example, 'contamination' is not specific. What is contaminated? The upstream and/or downstream meter run? The upstream and/or downstream surface of the plate? And if so, is the orifice plate sharp edge contaminated, or just the outer section of the plate? And what substance is contaminating the meter? Is it a solid scale that does not change shape as flow conditions change? Is it a Newtonian fluid, such as a trace amount of highly viscous oil? Or is it a non-Newtonian fluid, perhaps a pseudoplastic or Bingham plastic substance (such as grease or wax), where the distribution of the contaminant can slowly change with time and varying flow conditions? The term 'contamination' is too general to quantify. It is more of a group of issues than a specific issue.

Another example is disturbed inlet flow. How is the flow disturbed? Is it asymmetrical or swirling? Or both? Is the swirl clockwise or counter-clockwise? What is causing the disturbance? Is it a partially blocked flow conditioner? If so how is it blocked? Solid debris trapped and fixed in individual holes, for which there is a huge combination of possibilities? Or a pliable welders glove etc. where the blockage can change intermittently as flow conditions change and the debis moves around? In many cases due to space limitations meters are not installed with the advised upstream straight pipe length. So is a resulting flow disturbance steady or variable? That is, is it say, a fixed bend causing a repeatable steady disturbance, or is it say, a control valve that has variable settings and therefore variable disturbances? Again, the term 'disturbed inlet flow' is too general to quantify. It is more of a group of issues than a specific issue.

Some common meter problems are too general, i.e. not precisely enough defined, to specify a parameter that clearly quantifies them. Well defined specific meter malfunction sources, such as worn plate, buckled plate, etc., tend to have literature linking these quantifiable malfunctions to flow prediction biases. However, ill-defined, vague, non-specific meter malfunction sources, such as contamination and disturbed inlet flow, do not to have literature linking these unquantifiable malfunctions to flow prediction bias. Yes, there are published case studies where a given disturbance is recorded as having produced a given flow prediction bias, e.g. ISO TR 12748 shows test results of orifice meter plate contamination, but this is trivial. This does not offer any predictive powers whatsoever. The pertinent point is that for such undefined malfunction sources there is not surprisingly *a dearth of predictive eqautions*.

This limitation presently caps the capability of an orifice meter diagnostic system to estimate more types of problem's associated flow prediction biases. You first have to clarify a question before you can formulate a concise answer. That is, certain malfunction sources need to be better defined such that there is a quantifying parameter that can measure the magnitude of the problem. Only then is there a clear question, i.e. what effect does that specific magnitude of problem have on the flow prediction? This undoubtably will mean breaking general vague terms into more precisely definable quantifiable sub-terms.

For example, *specifically* inlet run contamination – modeled and described by say, symmetrical contamination ring thickness. Another example is *specifically* upstream plate contamination modeled and described by uniform contamination thickness. Reader Harris and Barton [4,8] have indeed modeled this as represented by Figure 30, and via CFD and experimentation offered an academic's expression for predicting a shift in C_d. In reality the C_d is set for an assumed correctly operating meter, and it is the flow prediction that shifts. Equation 28 shows the associated flow prediction equation ($p\%$).

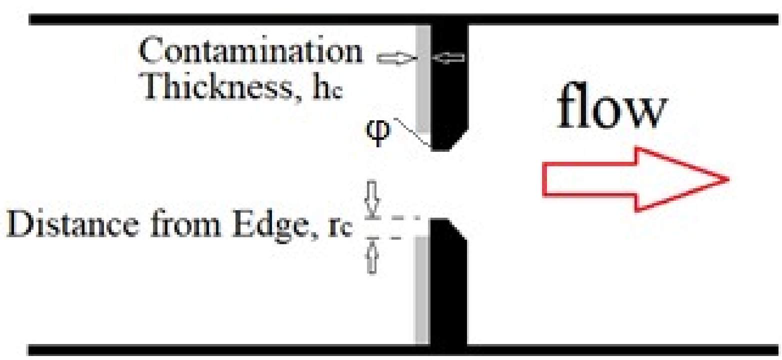

Fig 30. Schematic of Upstream Plate Contamination.

$$p\% \approx -22.8\left(\frac{h_c}{r_c}\right)^{1.4}\left(1-\frac{2r_c}{D(1-\beta)}\right)^4 \quad \text{-- (28)}$$

In practice the meter would have to be off-line to measure the contamination thickness 'h_c' and clearance distance 'r_c', although a single parameter defining the contamination magnitude would be better. Barton suggested the angle φ^o. However, even a succesfully derived relationship of say $\varphi^o=f(\eta\%)$ assumes that a diagnostic pattern recognition of 'contamination' is this *type* of contamination.

But this may be okay. Most contamination that coats a meter run tends to find its way on to the plate, and yet due to the high local fluid velocity close to the orifice edge the fluid tends to scour that region clean, as modelled in Figure 30. And, there are orifice meter run contamination data sets that show that small to moderate meter run contamination produces a surprisingly small flow prediction bias (e.g. Rabone et al [3]). Hence, although such a contamination model would be over simplistic, and therefore wrong, as the mathematician George Box stated "All models are wrong, but some are useful". And as the computing science researcher Pedro Domingos says "It is astonishing how simultaneously very wrong and very useful some models can be."

This contamination example highlights that although some common meter malfunction labels are presently not precisely defined enough to allow a single parameter to quantify them, it may be possible in some cases, through pragmatic reasoning, to produce a parameter that works well enough to correct this.

9. STATE OF THE ART FLOW METERING

There is a trend, a fashion, in flow metering sales and marketing to label the latest offering of a flow meter, or associated transmitter, with any new capabilities added to the system's hardware or firmware as a 'smart' meter or 'smart' transmitter.

The Oxford English Dictionary states 'smart' means 'showing a quick-witted intelligence'. Whereas there is no doubt modern computers used by flow meters are quick, they are not intelligent. They are the ultimate idiot savants, brillant at memory, repeatedly giving fast unimpeachable results to complex calculation routines. But, the term 'smart' meter literally means 'intelligent' meter, i.e. a meter that has the ability to itself *acquire* and apply knowledge and skills. Whereas computer science has of course made significant advances in the field of artificial intelligence no flow meter as yet has this ability, or anywhere close. The present metering systems marketed as 'smart' all have their so called 'acquired' skills not learned by the system itself, but by code added to firmware commands from people. It is the people, not the meter, that have done the learning, aquired the knowledge and applied that knowledge and skill to the meter's firmware. *All* the intelligence here comes from the people. State of the art flow metering systems remain insentinent, i.e. incapable of thought and understanding, and therefore they are decidedly *not* smart, regardless of labels slapped on them by sales and marketing departments. Furthermore, to add to the 'smart' metering hyperbole, seldom does a metering technology marketed as 'smart' involve firmware additions that hearld any true meter advance that can be called 'ground breaking'. The term is all too often applied to quite mundane algorithms that have been around in some form for decades – so caveat emptor.

Machine learning, where computers sieve through vast data sets and 'learn' from looking for patterns in the data is of course applicable to metrology. But as yet no mainstream commercial single phase flow meter design as yet applies significant meachine learning techniques. The cutting edge of flow metering is not yet the development of 'smart' meters, but rather the significant and useful advances in human learning that is being added to the flow computers firmware to make the insentinent system far more useful than ever before. This is the genuine state of the art, and it is this practice that is being discussion here.

10. CONCLUSIONS

Flow meter verification systems (powered by diagnostic suites) are very useful aids for flow meter terotechnology, i.e. the optimization of flow meter maintenance and operation, as well as being useful for auditing and lost and unaccounted for product calculations. Whereas it is beneficial to have a generic warning stating something is wrong, heuristic pattern recognition now increases the benefit of the system by specifically stating what is wrong, or at least short listing the meter problems that could cause such a result.

All flow meter diagnostic suites consist of a set of individual diagnostic tests that are either objective or subjective tests. The combined set of these diagnostic tests can produce a revealing diagnostic pattern. However, it is specifically the objective tests alone that hold the key to estimating the identified malfunction's associated flow predcition bias. Once pattern recognition has isolated the type of malfunction, the objective tests can be used to estimate the magnitude of that malfunction, and from there the associated flow prediction bias can be estimated.

Although theoretically there are an infinite amount of types, magnitudes, and combinations of orifice meter malfunctions, in the majority of cases the simplest solution is *probably* correct. Applying the concept of 'Occam's Razor' if you don't need to add complexity to explain a result then don't. Hence, with pattern recognition suggesting a probable singular malfunction type, one or more objective tests can be applied to then quantify the magnitude of that problem, and hence the corresponding flow prediction bias.

This principle has been developed by DP Diagnostics and proven on various different orifice meter malfunction data sets. Due to the 'nature of the beast' flow meter diagnostic suite technology is never complete, but just continually improved. Hence, although the system is not claimed to be perfect, it is now capable enough to be of considerable practical usefulness. And *a technology does not need to work perfectly all of the time to be of considerable practical use most of the time.*

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APPENDIX

COMPARATIVE REVIEW OF ULTRASONIC METER DIAGNOSTIC SUITE CONSTITUENT COMPONENTS

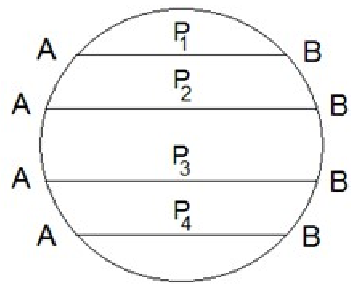

Fig A1. Schematic of 4 Path USM.

Ultrasonic flow meters (USMs) are known for having a comprehensive diagnostic suite. Let us consider the case of the popular four path USM (see Figure A1). There are commonly seven separate diagnostic tests within the USM diagnostic suite. These are:

1. Speed of Sound (SoS): A homogenous fluid has a constant SoS regardless of the local flow velocity. A by-product of each path's velocity reading is a SoS prediction. By physical law all individual path SoS predictions for the same homogenous fluid should be the same. Hence, the USM SoS check is ***objective***.

2 & 3. Flow Profile (FP) and Symmetry (S): The USM calibration records the FP and S characteristics. If these calibration results are transferrable to the field then these diagnostic tests are ***objective***. However, due to potential small unpredictable changes between calibration laboratory and the field ISO 17089 Ed 1 suggests setting these baselines as found during commissioning. This would make these diagnostic tests ***subjective***. It is a grey area if these values shift enough between calibration and field to practically lose their ***objective*** status.

4. Path Signal to Noise (SNR): SNR is monitored during USM calibrations, but this parameter is not transferable to the field, and is therefore ***subjective***.

5. Transducer Gain%: Transducer Gain% is monitored during USM calibrations, but this parameter is not transferable to the field, and is therefore ***subjective***.

6. Path Turbulence: Path Turbulence is monitored during USM calibrations, but this parameter is not transferable to the field, and is therefore ***subjective***.

7. Path Performance: Path Performance is monitored during USM calibrations, but this parameter is not transferable to the field, and is therefore ***subjective***.

Diagnostic Check	**Diagnostic Type**
Inter-comparison of Individual Path Speed of Sound	Objective
Flow Profile	Objective / Subjective?
Symmetry	Objective / Subjective?
Path Signal to Noise Ratio (SNR)	Subjective
Transducer Gain %	Subjective
Path Turbulence	Subjective
Path Performance	Subjective

Table A1. Ultrasonic Meter Diagnostic Tests Objective / Subjective Designation.

Table A1 summarizes the USM diagnostic test designations. The seven diagnostic USM tests are one objective, two possibly objective, and four subjetive tests.