

Orifice Meter Diagnostics – Predicting the Magnitudes of Flow Prediction Biases

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Abstract

With most modern flow meters there is a drive to equip the meter with a comprehensive verification system driven by a diagnostic suite. A diagnostic suite is a collection of different individual diagnostic checks grouped together to collectively offer more information. The state of the art is to use these diagnostic suites to show if the meter has a problem, and if so then use diagnostic suite pattern recognition to try to identify the source of the problem. However, there is virtually no R&D published that goes on to then try and predict the associated flow prediction bias induced by that identified malfunction. One such orifice meter diagnostic suite (commonly called 'Prognosis') is based on pressure field analysis. In this paper the development of Prognosis to show a problem exists, identify the source of the problem, and **then** predict the associated flow prediction bias is discussed..

1 Introduction

This paper discusses the capabilities of an orifice meter verification system. The DP Diagnostics verification system (Prognosis) uses a downstream pressure tap (e.g. see Fig 1) to access the information contained within the meter's entire pressure field. An automated system states in real time when the meter has a problem, and then by use of pattern recognition states what that problem is, or short lists the possible problems. The system is now being developed to also estimate the associated flow prediction bias of various common orifice meter malfunctions in real time.

2. State of the Art of Flow Meter Verification Systems

Flow meter users ask three things from the developers of flow meter diagnostic suites: 1) 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:



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

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 a diagnostic pattern. Abnormal diagnostic patterns can be matched to common malfunctions. However, the state of the art of such techniques 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 Prognosis orifice meter diagnostic system uses automated pattern recognition to supply a list of possible common malfunctions in order of their probability. Depending on the diagnostic 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 pattern is challenging. Little to nothing has been done on the follow on task of estimating the associated flow prediction bias for a predicted malfunction.

However, it has now been realised that such a system is possible for the orifice meter verification system. In practice, most flow meter malfunctions are caused by a relatively few common singular problems, and not combinations of complex rare problems. That is, it could be claimed that there is a Pareto Principle at work, i.e. an 80/20 rule, i.e. 80% of mis-measurements come from 20% of the possible malfunction sources.

On that point, an orifice meter verification system has now been developed that can identify specific single malfunction types, or short list a few single malfunction types that can cause specific diagnostic patterns, and then assign corresponding estimated flow prediction biases to each malfunction case.

3 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.

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 is 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 is 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 as 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 meagre kind. It is an ambiguous and imprecise diagnostic statement open to various interpretations. 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 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 identifies 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 values include instrumentation reading uncertainties. The stated 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. However, 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 'Prognosis' 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 (3rd) pressure port 6D downstream of the plate. As shown in Fig 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.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad (1)$$

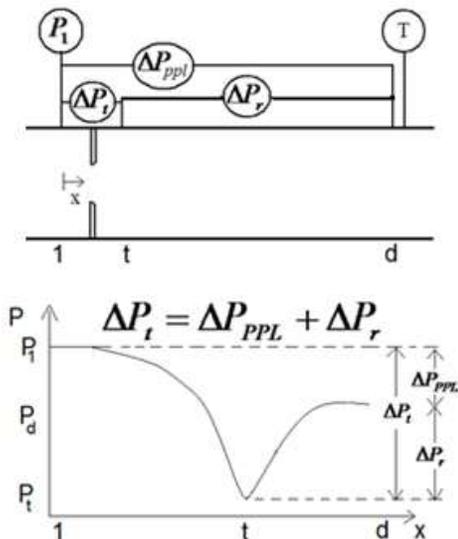


Fig 2. Orifice Meter with Instrumentation and Pressure Field Schematic.

Equation 1 (and Fig 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 reading, and hence the allowable difference between the inferred and read ΔP_t values is denoted as uncertainty $\theta\%$. The actual percentage difference is denoted as $\delta\%$ (see equation 2).

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

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.

Traditional / Primary Flow Equation:

$$m_t = \frac{A\beta^2}{\sqrt{1-\beta^4}} \varepsilon C_d \sqrt{2\rho\Delta P_t}, \pm x\% \quad (3)$$

Expansion Flow Equation:

$$m_r = \frac{A\beta^2}{\sqrt{1-\beta^4}} K_r \sqrt{2\rho\Delta P_r}, \pm y\% \quad (4)$$

PPL Flow Equation:

$$m_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}}, \pm z\% \quad (5)$$

Traditionally, there is a single DP meter flow rate calculation based on the traditional (i.e. primary) ΔP_t reading, i.e. equation 3. However, the additional two ΔP s give two extra flow prediction calculations, i.e. the expansion meter based on the recovered ΔP_r 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 primary, 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.

$$\beta = \sqrt{A_t / A} = d / D \quad (6)$$

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:

$$C_d = f(\beta, Re) \quad (7)$$

$$Re = 4m/\pi\mu D \quad (8)$$

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:

$$PLR_{base} = f(\beta) \quad (9)$$

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.:

$$K_r = (\epsilon C_d) / \sqrt{1 - PLR_{base}} \quad (10)$$

$$K_{PPL} = (\beta^2 / \sqrt{1 - \beta^4}) \cdot ((\epsilon C_d) / \sqrt{1 - PLR_{base}}) \quad (11)$$

Orifice meters with a downstream pressure tap are 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 inter-comparison of any two of the three mass flow rate predictions is an objective diagnostic check. 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 coefficient 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.

Primary to PPL Meter Comparison :	
$\psi\% = [(m_{PPL} - m_i)/m_i] * 100\%$	(12)

Primary to Expansion Meter Comparison:	
$\lambda\% = [(m_r - m_i)/m_i] * 100\%$	(13)

PPL to Expansion Meter Comparison:	
$X\% = [(m_r - m_{PPL})/m_{PPL}] * 100\%$	(14)

Primary/PPL Meter allowable difference:	
$\Phi\% = \sqrt{(x\%^2) + (z\%^2)}$	(15)

Primary/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.

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

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

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

All three 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 diagnostic checks*. The measurable quantities $\alpha\%$, $\gamma\%$, and $\eta\%$ represent the quantifiable difference between measured and baseline DP ratios (see equations 20 thru 22).

<p>PLR test: $\alpha\% = [(PLR_{read}/PLR_{base}) - 1] * 100\%$ (20)</p> <p>PRR test: $\gamma\% = [(PRR_{read}/PRR_{base}) - 1] * 100\%$ (21)</p> <p>RPR test: $\eta\% = [(RPR_{read}/RPR_{base}) - 1] * 100\%$ (22)</p>
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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.

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

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. Skelton [2] describes the methodology in considerably more detail.

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

Table 1. The DP Meter Diagnostic Results.

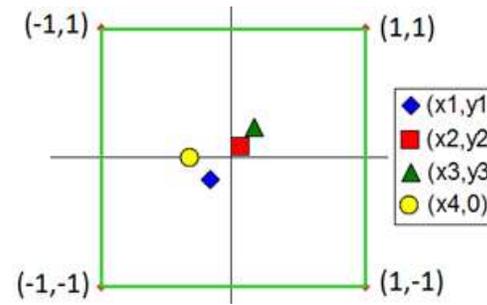


Fig 3. Normalized Diagnostic Box (NDB) Display.

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 [3]. 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 (Fig 3) but it is accounted for in the background pattern recognition capabilities.

Diagnostic Check	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 diagnostic test in the diagnostic suite it is a very useful addition for pattern recognition. For example, wet gas flow, a blocked impulse line, and erroneous high orifice diameter keypad entry all produce the same *average* diagnostic pattern. However, this subjective test on the instrumentation dynamic behaviour 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.

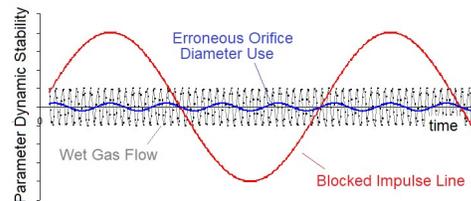


Fig 4. Orifice Meter Parameter Stability (Subjective Diagnostic Test) for Three Different Malfunction Sources.

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. Estimating Flow Biases

Presently there are a few limited sporadic academic publications that discuss in a quantitative way 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. However, in order to use this information an orifice meter operator would need to know the meter has a malfunction, and what the specific type and severity of that malfunction was.

An orifice meter diagnostic system that could indicate something was wrong, then what specifically was wrong, and then what the magnitude of that malfunction was, and then estimate the corresponding flow prediction bias, would be beneficial. Such an automated system 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. an objective) diagnostic technique *must* be used.

Fig 5 shows how a 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 malfunction, one or more of the quantifiable objective diagnostic test results must be relatable to the magnitude of that malfunction (see upper graph). Secondly, the magnitude of malfunction must be relatable to the flow prediction

bias (see lower graph). Then the objective test result is related to the flow prediction bias.

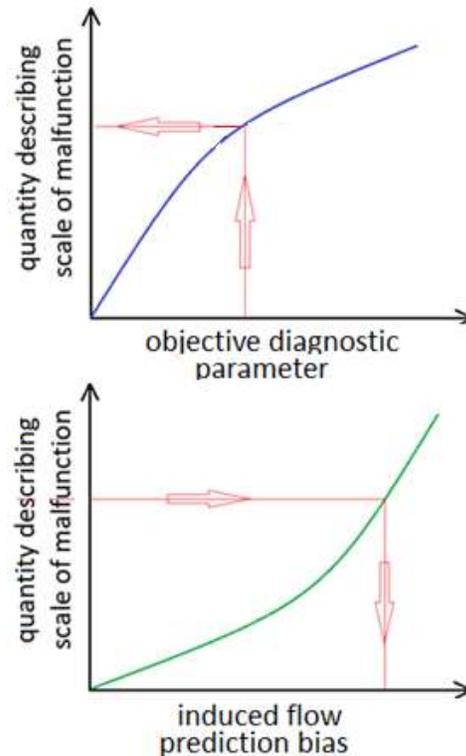


Fig 5. Diagnostic System Malfunction Magnitude and Associated Flow Prediction Bias Estimation.

DP Diagnostics has gathered various common malfunction orifice meter data from various laboratories, field tests, and actual service meters. DP Diagnostics has now developed the system to estimate the magnitude of various identified malfunctions and the corresponding flow prediction bias. The following worked examples help explain the concept, and the surprising simplicity of the method.

7. Worked Examples

7.1 Erroneous DP Readings

Fig 6 shows a serviceable 10", 0.46β, orifice meter. Fig 7 shows this meter's diagnostic display. A slight leak on the primary (DP₁) DP transmitter's 5 way manifold equalization valve was then deliberately introduced.

Fig 8 shows the resulting diagnostic pattern. 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 primary (traditional) DP reading as the malfunction source. That is, one or more point/s outside the box indicates something is wrong. The x_4 point shows the issue is with the DP transmitters. The remaining



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

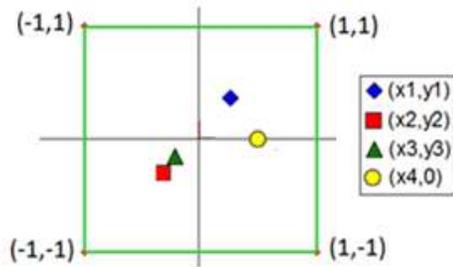


Fig 7. 10" Orifice Meter Diagnostic Result of Correctly Operating System.

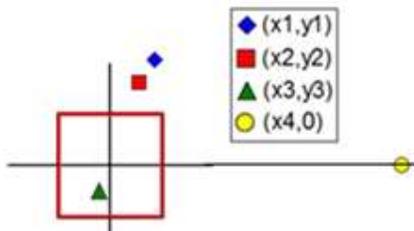


Fig 8. 10" Orifice Meter Diagnostic Result with Erroneous DP_t Reading..

pattern shows (x_3, y_3) , i.e. the recovered and PPL DP readings, have no problem. The two points (x_1, y_1) and (x_2, y_2) are both outside the NDB and their communal DP transmitter is that reading the primary (traditional) DP. Hence this DP reading is erroneous. But how 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 shows that the inferred $\Delta P_{t,inf} = 64.56''WC$ is correct and can therefore be compared to the directly read (and known to be erroneous) $\Delta P_t = 61.08''WC$. Thus, the objective diagnostic test tells us that the direct ΔP_t reading has a quantifiable -5.4% bias.

$$p\% = \left\{ \left(\frac{m_{t,bias}}{m_{t,correct}} \right) - 1 \right\} * 100\%$$

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

Equation 23 shows the associated gas flow prediction bias ($p\%$), calculation. In this example the bias is found to be -2.7%. Figs 9 and 10 show the relationship between the objective diagnostic 'x4' vs. Malfunction Quantity vs. Flow Prediction Bias.

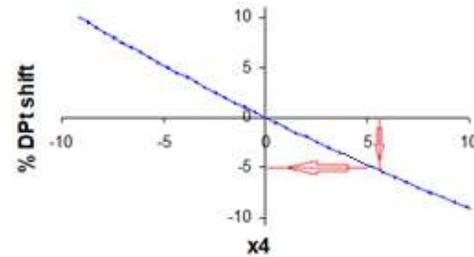


Fig 9. Meter Objective Diagnostic vs. ΔP_t Reading Bias

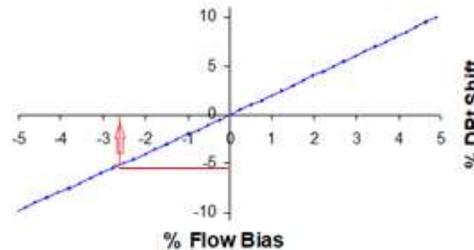


Fig 10. ΔP_t Reading Bias vs. Flow Prediction Bias.

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 $\approx -2.7\%$.

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 Orifice Diameter

A potential problem with orifice meters is erroneous keypad entry geometries to the flow computer. Traditionally this goes unnoticed, but the use of an orifice meter diagnostic suite can now warn of a problem, and offers a short list of possible causes that includes 'erroneous orifice diameter'.

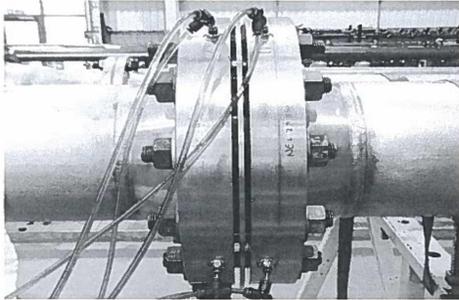


Fig 11. 4", 0.6 β Orifice Meter

A 4", sch 40, 0.6 β paddle plate orifice meter was tested at a water flow facility (see Fig 11). Inlet and orifice diameters were 4.026", and 2.416" respectively. Flow was 19.42 kg/s with $DP_t = 51.54\text{kPa}$, $DP_r = 18.75\text{kPa}$ and $DP_{PPL} = 32.74\text{kPa}$. This produced a read PLR of 0.6363, an ISO C_d prediction of 0.607, and a PLR baseline prediction of 0.635. The flow prediction and reference agreed to $<0.5\%$, i.e. the orifice meter was serviceable.

Consider the case where the orifice diameter was erroneously entered as 2.516". Fig 12 shows the diagnostic suite's response for the correct geometry. Fig 13 shows the response for the erroneous orifice diameter. The pattern is indicative of a few possible malfunction sources, but excludes all other 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.

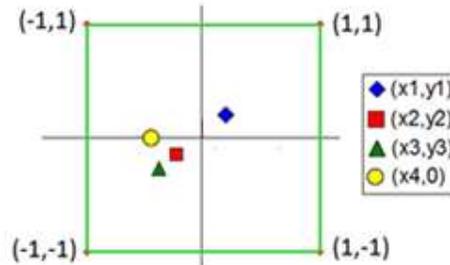


Fig 12. Correctly Operating Orifice Meter

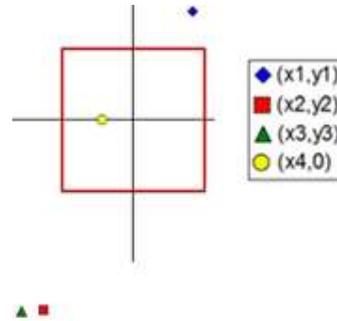


Fig 13. High Orifice Diameter Entry.

The keypad entered geometry suggests $\beta = d/D = 2.516" / 4.026" = 0.625$. Select objective diagnostic $\alpha\%$, i.e. 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 the read PLR is in effect a measure of the actual beta, i.e. reverse equation 9.

$$\beta = d/D = f(PLR_{read}) = f(0.6363) = 0.6003$$

The resulting beta is 0.6003. Hence, the actual orifice diameter is estimated as:

$$d = D\beta = 4.026" * 0.6003 = 2.417"$$

The erroneous orifice diameter induced flow prediction bias ($p\%$) can now be directly calculated, see equation 24.

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

The erroneous beta is $\beta_{baised} = 0.625$, and the predicted beta is $\beta_{baised} = 0.6004$. In

this worked example for simplicity it is reasonably assumed that $(\epsilon C_d)_{biased} \approx \epsilon C_d$, however in practice flow computer

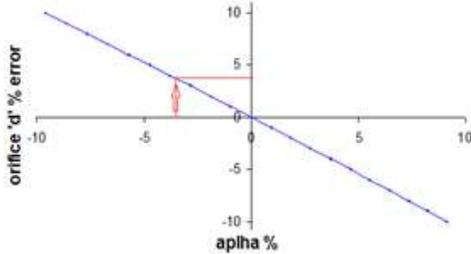


Fig 13. Objective Diagnostic vs. Orifice 'd' Bias. vs. Flow Prediction Bias.

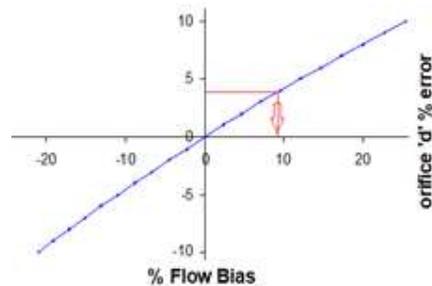


Fig 14. Orifice 'd' Bias. vs. Flow Prediction Bias.

software would also calculate this second order effect. Equation 24 therefore estimates the flow prediction bias ($p\%$) induced by the erroneous orifice diameter as $\approx +9.8\%$. Fig 13 shows the objective diagnostic parameter $\alpha\%$ being used to predict the magnitude of the source of the problem (i.e. the percentage bias in the orifice diameter). Fig 14 shows the resulting diameter bias being converted to an associated percentage flow prediction bias.

7.3 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 unnoticed, but use of diagnostic suite now warns of a problem, and offers a short list of possible causes that includes 'worn edge'.

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, modelling the wear as a symmetrical chamfer with height

l depth ' l ', i.e. as a wear height (l) to orifice diameter ' d ', (l/d ratio), see Figure 15,

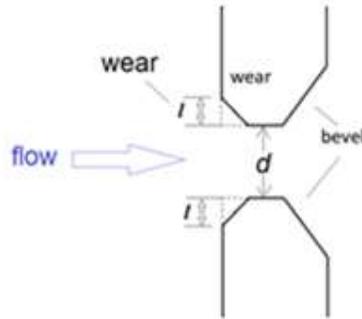


Fig 15. Modelling Orifice Plate Edge

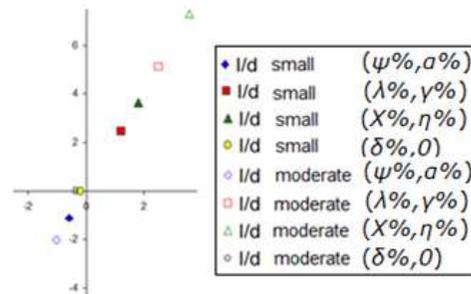


Fig 16. Sample Orifice Meter Diagnostic Data for Worn Edge.

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 $r \approx l$ 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 17 and 18. DP Diagnostics recorded the worn edge (l/d) vs. objective diagnostic values vs. flow prediction bias ($p\%$) data. Figure 16 shows the description of the edge wear and sample un-normalised diagnostic data.

Figure 16 show the un-normalized objective diagnostic results ($\psi\%, \alpha\%$), ($\lambda\%, \gamma\%$), ($X\%, \eta\%$), and ($\delta\%, 0$). Whereas the DP reading integrity check ($\delta\%$) 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).



Fig 17. Filed Induced Wear on Edge.



Fig 18. Chamfered Lathe Induced Wear on Edge.

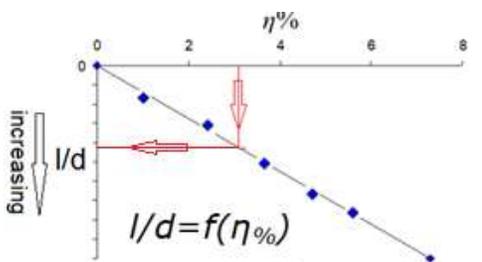


Fig 19. Objective Diagnostic vs. Amount of Edge Wear

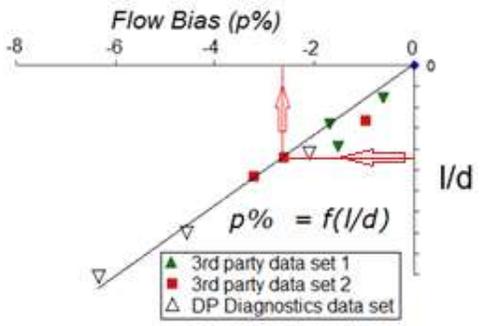


Fig 20. Amount of Edge Wear vs. Flow Prediction Bias.

Figure 19 shows orifice edge wear (l/d) vs. measured objective diagnostic $\eta\%$ 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 21 shows the similarity of the DP Diagnostics data to the 3rd party data published by Reader-Harris [4].

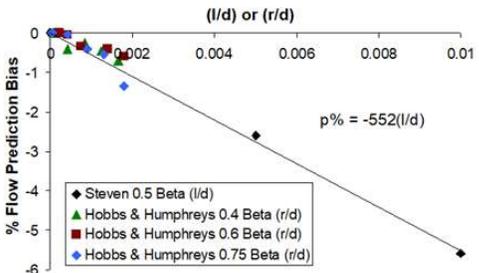


Fig 21. 3rd Party and DP Diagnostics Edge Wear vs. %Flow Prediction Bias ($p\%$).

The existence of 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 magnitude of the wear then manually measured. Only then can the associated flow prediction bias can be estimated. 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.

7.4 Backwards / Reversed Orifice Plate

Many orifice plate designs are not symmetrical, they have a bevel on the back face (e.g. see Fig 22). A common operational mistake is to install the orifice plate backwards. 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



Fig 22. View of an Orifice Plate Back Face.

specific beta a backward plate always produces the same predictable step shift in all six diagnostic parameters (the seventh x_4 being unaffected). The diagnostic pattern (inclusive of actual coordinates) is specific to backwards plates.

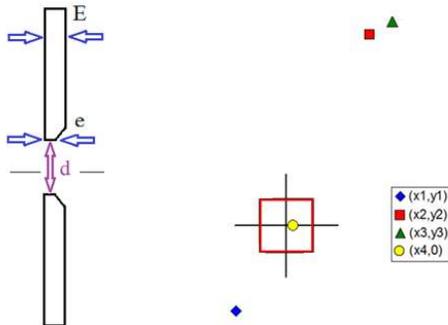


Fig 23. Sketch of Plate and Diagnostic Suite Reversed Plate Pattern.

There are various published calculation routines that estimate the flow prediction bias induced by a backwards plate. Reader-Harris [4] gives equations 25 and 26. 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 $e/E > 0.5$:

$$p\% = -18.93 + 12.91\beta - 34.04 \frac{E}{D} - 8.9 \frac{e}{E} + 13.64 \left(\frac{e}{E} \right)^2 \quad (25)$$

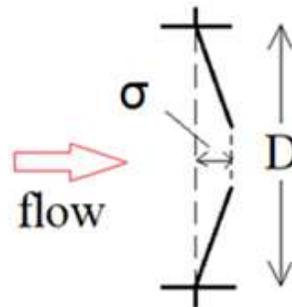
Researcher Reader-Harris suggests for $e/E \leq 0.5$:

$$p\% = -\left(17.2 - 10.4\beta^{2.5}\right) * \left(1 - \exp\left(\frac{-1270 \frac{(E-e)}{d}}{17.2 - 10.4\beta^{2.5}}\right)\right) \quad (26)$$

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.

7.5 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'. Fig 24 shows the diagnostic result for a small and then moderate plate buckle.



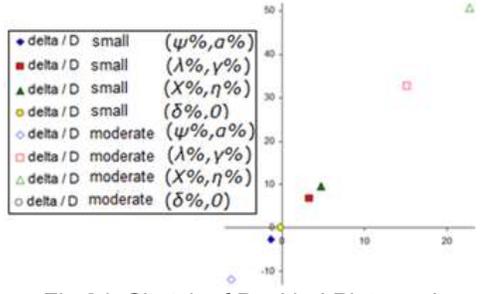


Fig 24. Sketch of Buckled Plate and Diagnostic Suite Buckled Plate Pattern.

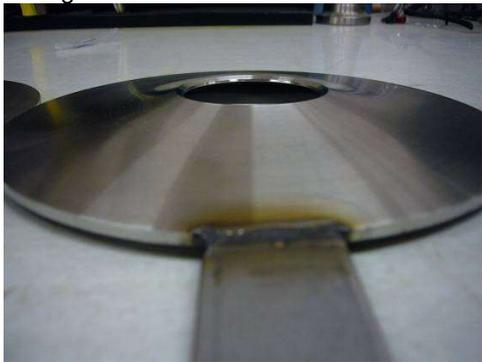


Fig 25. Moderately Buckled Plate.



Fig 26. Severely Buckled Plate.

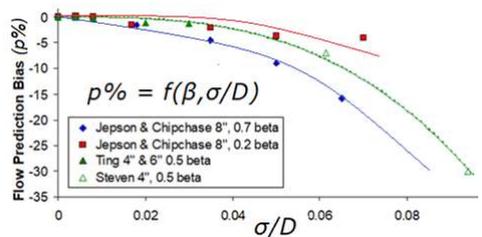


Fig 27. Buckle Magnitude vs. Flow Prediction Bias Data.

When discussing orifice plate buckling it is necessary to choose a parameter to quantify the magnitude of the buckle. Let us model the buckle as a symmetrical

buckle of depth 'sigma' to meter inlet diameter 'D', (i.e. a sigma/D ratio), see Figure 24.

Over several years DP Diagnostics tested buckled plates in laboratories with varying degrees of buckle, e.g. see Figs 25 & 26. This buckled plate magnitude (sigma/D) vs. flow prediction bias (p%) data is similar to the limited 3rd party data sets (see sample data in Figure 27). The buckle (sigma/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 (beta) and known magnitude of buckle (sigma/D). DP Diagnostics recorded the buckle (sigma/D) vs. objective diagnostic values vs. flow prediction bias (p%) data.

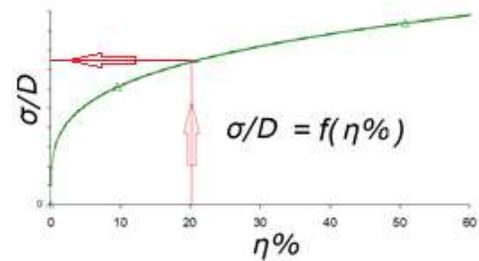


Fig 28. Objective Diagnostic Parameter (eta%) vs. Buckled Plate (sigma/D)

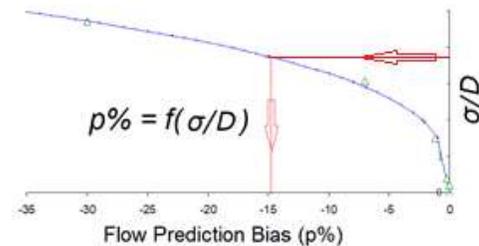


Fig 29. Buckled Plate (sigma/D) vs. Flow Prediction Bias (p%).

Fig 24 shows that various objective diagnostic checks have a relationship with the magnitude of a plate buckle. In this case the RPR objective diagnostic check is the most sensitive, i.e. eta% vs. sigma/D value (although the any of the six could be successfully used). Fig 28 shows, for a fixed beta, orifice plate diagnostic result eta% can be related to the buckle magnitude (sigma/D). Fig 29 shows that once the buckle magnitude is estimated the associated flow prediction bias can be predicted through the DP Diagnostics data fit p%=f(beta, sigma/D).

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 challenging 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' or 'disturbed flow' are not specific. What is contaminated? The upstream and / or downstream meter run? The upstream and/or downstream surface of the plate? And what substance is the contaminant, solid or fluid? What sort of flow disturbance is there? Asymmetrical or swirl flow? And how is it asymmetrical, and if its swirling in what direction? Terms like 'contaminated' or 'disturbed' flow are too vague, too general to quantify. They are more of a group of issues than a specific issue.

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, perhaps unsurprisingly, ill-defined, vague, non-specific meter malfunction sources, such as contamination and disturbed inlet flow, do not have literature linking these unquantifiable malfunctions to flow prediction bias. Yes, there are published case studies where a given contamination or disturbance is recorded as having produced a given flow prediction bias. But this is of little use to predicting how the bias changes as the problem increases or decreases in severity. That is, such data offers little predictive power. The pertinent point is that for such undefined malfunction sources there is not surprisingly a *dearth of predictive equations*.

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 undoubtedly will mean breaking general vague terms into more precisely definable quantifiable sub-terms.

10. Conclusions

Flow meter verification systems (powered by diagnostic suites) are very useful aids for optimization of flow meter maintenance and operation. They are also 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 prediction 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.

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.

11. References

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4. Reader-Harris M. "Orifice Plates and Venturi Tubes", Published by Springer 2015, ISBN 978-3-319-16879-1.