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Flow Disturbance Cone Meter Testing

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1. Introduction

The cone meter is a generic Differential Pressure (DP) meter design. It operates according to the same physical principles as other DP meters, such as orifice, nozzle and Venturi meters etc. A cone meter is shown in Fig 1, with a cut away to reveal the DP producing cone 'primary element'.

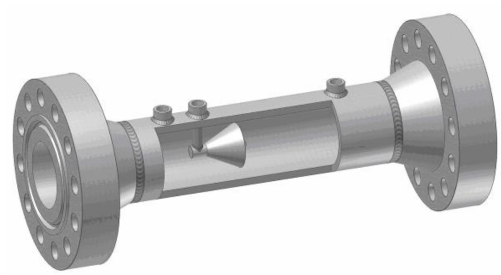

Figure 1: Sectioned view of a Cone Meter (flow is left to right)

Piping components can induce asymmetry and swirl in flow. This 'disturbed flow', i.e. asymmetrical and swirling flow, is known to induce flow rate prediction biases in many flow meter outputs. Most flow meters have required minimum upstream/downstream straight pipe lengths to mitigate disturbed flow. A flow conditioner mitigates disturbed flow and reduces the minimum upstream and downstream straight pipe lengths required by many flow meter designs.

Cone meters have grown in popularity due to their claimed immunity to flow disturbances. Cone meters are said to require no flow conditioning and little upstream and downstream straight pipe lengths. If this is true, cone meters can be installed in many locations where no other flow meter could operate satisfactorily. A meter that is immune to flow disturbances is of significant importance to industry. Hence, independent proof of cone meter resistance to flow disturbances is important. However, there is little literature in the public domain discussing cone meter performance in disturbed flows.

2. Background to Cone Meter Reaction to Flow Disturbances

The cone meter patent expired in 2004 and the generic cone meter design is now offered by several suppliers. Some manufacturers claim that the meters immunity to flow disturbances stems from the cone acting as a flow conditioner. That is, the meter is said to have inbuilt flow conditioning.

Figures 2 & 2a show sample diagrams from cone meter manufacturer's literature. In both cases, the literature states that the cone "flattens the velocity profile", i.e. mitigates asymmetric flow, upstream of the cone. It is certainly true that flow acceleration is

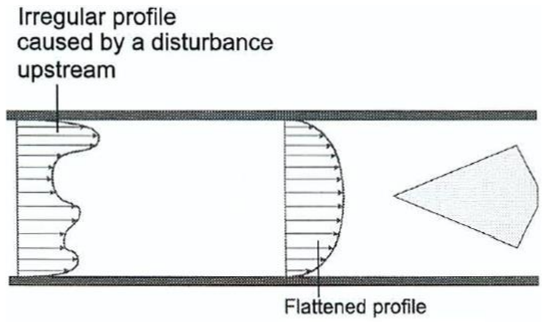

Figure 2. Manufacturer 1 Diagram.

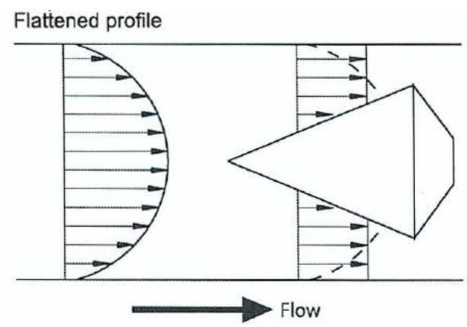

Figure 2a. Manufacturer 2 Diagram.

known to be a good mechanism for flattening a velocity profile, i.e. mitigating asymmetric flow effects. However, there has yet to be a rigorous scientific explanation on why a cone element would be significantly more efficient at mitigating asymmetrical flow effects than other primary element shapes. Furthermore, the public literature or debate does not offer any rigorous explanation (other than occasional non-detailed verbal comments about conservation of angular momentum) as to why a cone meter would perhaps be more resistant to swirl than other DP meter design. Nevertheless, regardless of *why* a cone meter is resistant to flow disturbances, there is independent research by various parties which shows that cone meters *are* resistant to flow disturbances.

In 2004 McCrometer [1] showed 4", 0.6 beta ratio (β) cone meter resistance to flow disturbances by testing a cone meter with the moderate flow disturbance tests required by API MPMS 22.2 [2]. In 2009 DP Diagnostics [3] showed 4", 0.63β cone meter resistance to flow disturbances by testing the cone meter with various moderate and extreme flow disturbances. In 2010 SolartronISA [4] discussed cone and Venturi meter resistance to moderate flow disturbances. SolartronISA showed the flow disturbance resistance capabilities of both 0.6β and 0.85β cone meters. This was the first time a high beta ratio cone meter (i.e. $\beta > 0.63$) had been tested with flow disturbances and the results publicly released. Whereas the three independent mid-size cone / beta ratio data sets showed the cone meter to be immune to flow disturbances, the SolartronISA 6", 0.85β cone meter results hinted at a beta ratio effect. The larger beta ratio (i.e. the smaller cone relative to the pipe size) appeared to have a slightly degraded resistance to flow disturbances.

Cone meter resistance to flow disturbances being dependent on beta ratio would be in line with Venturi meter performance. ISO 5167–Part 4 [5] shows a table of minimum upstream lengths for a Venturi meter with various upstream components (i.e. different disturbances). The ISO indicate that a Venturi meter's resistance to flow disturbance is beta ratio dependent. The higher the Venturi meter beta ratio, the longer the required upstream straight pipe length, i.e. the more susceptible the Venturi meter is to flow disturbance. Furthermore, if the cone meter does obtain a high level of flow disturbance immunity through the cone acting as a flow conditioner, it would stand to reason that the smaller the cone relative to the meter body size (i.e. the larger the beta ratio) the less conditioning, and the less resistance the cone meter would have to upstream disturbances.

In 2012 ConocoPhillips (COP) approached CEESI enquiring about high beta ratio cone meter flow disturbance tests. CEESI owned a standard design 4", sch 80, 0.75β cone meter (see Figure 22). As this meter was readily available for use, the beta ratio was suitably high to investigate high beta ratio cone meter disturbed flow resistance characteristics, and the 0.75β cone meter size was very popular in industry, COP decided to utilize this meter. Although testing this 0.75β advanced knowledge of cone meter flow disturbance characteristics, COP was and is aware that some cone meter manufacturers offer $\beta \leq 0.85$, and claim flow disturbance immunity across the entire beta ratio range. Therefore, the following test results are not to be considered conclusive. Further investigation is required before a comprehensive understanding of cone meter resistance to flow disturbances is achieved.

As the 4", 0.75β cone meter was manufactured by DP Diagnostics, it had a downstream pressure tap on the meter body (e.g. see Figure 1). The patented DP meter diagnostic system ('Prognosis') was potentially available. This allowed COP to test both the cone meters resistance to flow disturbances and the diagnostic systems operation when the cone meter was subjected to flow disturbances**.**

3. Cone Meters and DP Diagnostics Self-Diagnostic Operating Principles

Figure 3 shows a cone meter with instrumentation and the (simplified) pressure fluctuation (or "pressure field") through the meter body. Traditional DP meters read the inlet pressure (P_1), the downstream temperature (T) and the differential pressure (ΔP_t) between the inlet pressure tap (P_1) and a pressure tap positioned in the vicinity of the point of low pressure (P_t). That is, traditional DP meter technology only takes a single DP measurement from the pressure field.

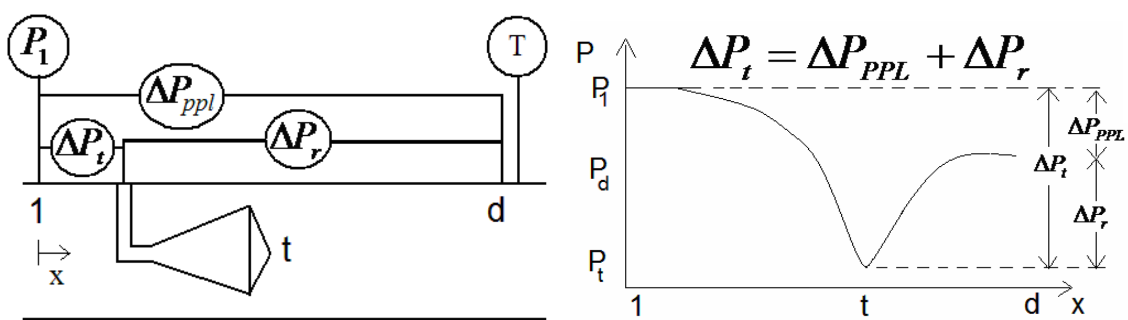

Fig 3: Cone Meter with Instrumentation and Pressure Fluctuation Graph.

A pressure tap (P_d) downstream of the cone allows extra pressure field information to be read. The DP between the downstream (P_d) and the low (P_t) pressure taps (or "recovered" DP, ΔP_r), and the DP between the inlet (P_1) and the downstream (P_d) pressure taps (i.e. the permanent pressure loss, 'PPL', ΔP_{PPL}) can be read. The sum of the recovered DP and the PPL **must** equal the traditional differential pressure (equation 1).

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

The traditional flow rate equation is shown as equation 2. The additional downstream pressure tap allows an extra two flow rate equations to be produced. The recovered DP can be used to find the flow rate with an "expansion" flow equation (see equation 3) and the PPL can be used to find the flow rate with a "PPL" flow equation (see equation 4). Note $\dot{m}_t$, $\dot{m}_r$ and $\dot{m}_{PPL}$ represents the traditional, expansion and PPL mass flow rate

Traditional Flow Equation: $\dot{m}_t = EA_t \varepsilon C_d \sqrt{2\rho\Delta P_t}$, uncertainty x% --- (2)

Expansion Flow Equation: $\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r}$, uncertainty y% --- (3)

PPL Flow Equation: $\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}}$, uncertainty z% --- (4)

equation predictions of the actual mass flow rate ($\dot{m}$) respectively. The symbol ρ represents the inlet fluid density. Symbols E , A and A_t represent the geometric constants of the velocity of approach, the inlet cross sectional area and the minimum (or "throat") cross sectional area through the meter respectively. The parameter ε is an expansion factor accounting for gas density fluctuation. (For liquids ε =1.) The terms C_d , K_r & K_{PPL} are the discharge coefficient, expansion coefficient and PPL coefficients respectively.

These three flow coefficients can be found by calibration. Each can be set as a constant with a set uncertainty rating, or, each may be fitted to the Reynolds number, usually at a lower uncertainty rating. The Reynolds number is expressed as equation 5. Note that μ is the fluid viscosity and D is the inlet diameter. In the case of a flow coefficient being fitted to the Reynolds number, as the Reynolds number (Re) is flow rate dependent, each of the three flow rate predictions must be independently obtained by an iterative method. A detailed derivation of these three flow rate equations is given by Steven [6].

$$\mathrm{Re} = \frac{4\dot{m}}{\pi\mu D} \quad \text{--- (5)}$$

Every cone meter body is in effect three flow meters. There are three flow rate equations predicting the same flow rate. Thus there are now effectively two check meters in series with the traditional flow meter. The flow rates can be inter-compared to create diagnostics. Naturally, all three flow rate equations have individual uncertainty ratings (say x%, y% & z% as shown in equations 2 through 4). Therefore, even if a cone meter was operating correctly, the flow predictions would not match *precisely*. However, a correctly operating meter should have no discrepancy between any two flow rate predictions greater than the root mean square value of the two flow prediction uncertainties. The maximum allowable difference between any two flow rate equations, i.e. $\phi\%$, $\xi\%$ & $\upsilon\%$ is shown in equation set 6a to 6c.

Traditional & PPL Meters % allowable difference $\phi\% = \sqrt{(x\%)^2 + (z\%)^2}$ -- (6a)

Traditional & Expansion Meters % allowable difference: $\xi\% = \sqrt{(x\%)^2 + (y\%)^2}$ -- (6b)

Expansion & PPL Meters % allowable difference: $\nu\% = \sqrt{(y\%)^2 + (z\%)^2}$ -- (6c)

If the percentage difference between any two flow rate predictions is less than the allowable uncertainties, then no potential problem is found. If the percentage difference between any two flow rate equations is greater than the allowable uncertainties, then this

Traditional to PPL Meter Comparison : $\psi\% = \left\{ \left(\dot{m}_{PPL} - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ -- (7a)

Traditional to Expansion Meter Comparison: $\lambda\% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} * 100\%$ -- (7b)

PPL to Expansion Meter Comparison: $\chi\% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} * 100\%$ -- (7c)

indicates a metering problem and the flow rate predictions should not be trusted. The three flow rate percentage differences are calculated by equations 7a to 7c.

The three DP ratios can be used directly for diagnostics purposes. The **P**ressure **L**oss **R**atio (or "PLR") is the ratio of the PPL to the traditional DP. The PLR value is a characteristic for cone meters operating with single phase homogenous flow. It can be expressed as a constant value, or related to the Reynolds number. We can rewrite Equation 1:

$$\frac{\Delta P_r}{\Delta P_t} + \frac{\Delta P_{PPL}}{\Delta P_t} = 1 \quad \text{--- (1a)} \qquad \text{where} \qquad \frac{\Delta P_{PPL}}{\Delta P_t} \text{ is the PLR.}$$

PPL to Traditional DP ratio (PLR): $(\Delta P_{PPL} \;/\; \Delta P_t)_{calibration}$, uncertainty a%

Recovered to Traditional DP ratio (PRR): $(\Delta P_r \;/\; \Delta P_t)_{calibration}$, uncertainty b%

Recovered to PPL DP ratio (RPR): $(\Delta P_r \;/\; \Delta P_{PPL})_{calibration}$, uncertainty c%

From equation 1a, if PLR is a set value (for any given Reynolds number) then both the **P**ressure **R**ecovery **R**atio or "PRR", (i.e. the ratio of the recovered DP to traditional DP) and the **R**ecovered DP to **P**PL **R**atio, or "RPR" must also be set values. All DP ratios available from the three DP pairs are constant values for any given cone meter geometry and Reynolds number. These three DP ratios can be found by calibrating the DP meter.

DP ratios found in service can be compared to expected values. The expected values are obtained from the meter calibration. Let us denote the percentage difference between the actual PLR and the expected value as $\alpha\%$, the difference between the actual PRR and the expected value as $\gamma\%$, and the difference between the actual RPR and the corrected value as $\eta\%$. These values are found by equations 8a to 8c.

$$\alpha\% = \{[PLR_{actual} - PLR_{calibration}] / PLR_{calibration}\} * 100\% \quad \text{--- (8a)}$$

$$\gamma\% = \{[PRR_{actual} - PRR_{calibration}] / PRR_{calibration}\} * 100\% \quad \text{--- (8b)}$$

$$\eta\% = \{[RPR_{actual} - RPR_{calibration}] / RPR_{calibration}\} * 100\% \quad \text{--- (8c)}$$

If the percentage difference between the in-service and expected DP ratio is less than the stated uncertainty of that expected DP ratio value, then no potential problem is found. If the percentage difference between the in-service and expected DP ratio is greater than the stated uncertainty of that expected DP ratio value, then a potential problem is found, and the flow rate predictions should not be trusted. With three DP ratios, there are three DP ratio diagnostic checks.

Equation 1 holds true for all generic DP meters (even after physical damage) allowing a dedicated DP reading diagnostics check. Therefore, any result suggesting that it does not hold true is an indication of false DP readings (regardless of whether the meter body is serviceable or not). The traditional DP (ΔP_t) can be inferred by summing the read recovery DP (ΔP_r) and permanent pressure loss (ΔP_{PPL}). This gives an inferred traditional DP ($\Delta P_{t,inf}$) that can be compared to the directly read traditional DP ($\Delta P_{t,read}$). Whereas theoretically these values are the same, due to the uncertainties of the three DP transmitters, even for correctly read DPs, they will be slightly different. The percentage difference ($\delta\%$) can be calculated as seen in equation 9.

$$\delta\% = \{(\Delta P_{t,\inf} - \Delta P_{t,read}) \ / \ \Delta P_{t,read} \} * 100\% \quad \text{--- (9)}$$

The uncertainty rating of each DP reading will be known. A maximum allowable percentage difference ($\theta\%$) between the directly read and inferred traditional DP values can be assigned. If the percentage difference between the directly read and inferred traditional DP values ($\delta\%$) is less than the allowable percentage difference ($\theta\%$), then no potential problem is found. However, if this percentage difference ($\delta\%$) is greater than the allowable percentage difference ($\theta\%$), then a problem with the DP measurements is confirmed and the flow rate predictions cannot be trusted.

Table 1 shows the seven situations that would signal a cone meter system warning. For convenience we use the following naming convention:

Normalized flow rate inter-comparisons: $x_1 = \psi\%/\phi\%$, $x_2 = \lambda\%/\xi\%$, $x_3 = \chi\%/\upsilon\%$

Normalized DP ratio comparisons: $y_1 = \alpha\%/a\%$, $y_2 = \gamma\%/b\%$, $y_3 = \eta\%/c\%$

Normalized DP sum comparison: $x_4 = \delta\%/\theta\%$

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_r **&** ΔP_{ppl}	$-1 \le x_3 \le 1$	$-1 < x_3$ 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. DP meter - possible diagnostic results.

For practical real time (or historical auditing) use, a graphical representation of the diagnostics continually updated on a PC screen (while being archived) can be simple and effective. A graph can be created with a normalized diagnostic box (or "NDB") with corner co-ordinates: (1, 1), (1, -1), (-1, -1) & (-1, 1). On such a graph, meter diagnostic points can be plotted, i.e. (x_1, y_1), (x_2, y_2), (x_3, y_3) & (x_4, 0), as shown in Figure 4.

If all points are within the NDB the operator sees no metering problem and the traditional meters flow rate prediction can be trusted. However, if one or more of the points falls

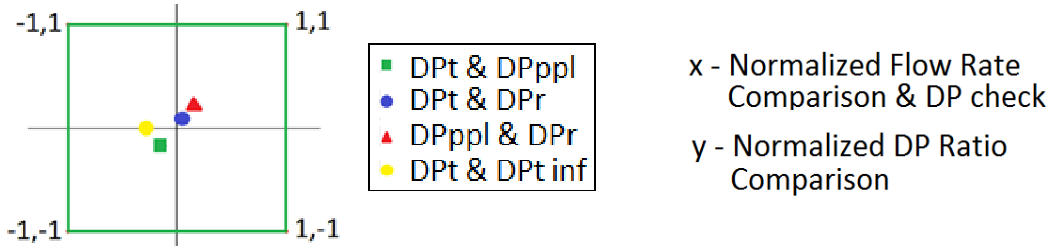

Figure 4. Normalized diagnostic box with diagnostic results

outside the NDB, the operator has an indication that the meter is ***not*** operating correctly and that the meters traditional (or any) flow rate prediction cannot be trusted. If the point (x_4, 0) falls out with the NDB, regardless of the other three diagnostic point locations, this is a statement that there is a DP reading problem. If one or more of the (x_1, y_1), (x_2, y_2) & (x_3,y_3) points fall outside the NDB, while (x_4, 0) remains within the NDB, this infers that there is a meter body malfunction. The particular pattern of a diagnostic warning in some cases indicates a particular problem, and in other cases short-lists the problems that produce such a diagnostic pattern.

Although these diagnostics have been described with respect to cone meters they are applicable to, and have been applied to other DP meters. The Intellectual Property holders, DP Diagnostics have partnered with Swinton Technology to create the commercial product ‘Prognosis’.

3a. Discussion on a Common Misperception Regarding ‘Prognosis’

Prognosis operates by comparing DP meters ‘found’ to ‘expected’ performances. Equally, it could be said that Prognosis operates in reverse by comparing the ‘expected’ to ‘found’ performances. The expected performance is set by the DP meter calibration (or, in the case of an orifice meter, from information derivable from statements in the ISO standards). The diagnostics indicate a problem when there is a significant mis-match between the “found- to-expected” performance (or “expected-to-found” performance).

DP Diagnostics has become aware that some engineers have mistakenly assumed that the integrity of Prognosis is dependent on the correctness of the calibrated performance criteria entered into the diagnostic system. They have assumed that an incorrect entered calibration / expected performance will compromise the integrity of the diagnostic system. **This is not true**.

Prognosis does not make any limiting assumption that either the ‘expected’ performance or the ‘found’ performance must be the correct performance with which the other can be compared and judged. This diagnostic method considers neither the ‘found’ performance nor the ‘expected’ performance to be automatically trustworthy. If there is a significant mis-match between the found-to-expected (or expected-to-found) performance, regardless of the reason for the mis-match, the diagnostics *correctly* indicate that a problem exists.

For a DP meter system to operate correctly two conditions must be met:

1) The correct meter geometry and performance characteristics (e.g. discharge coefficient) must be used with equation 2, i.e. the traditional flow rate equation.

2) The DP meter system must be fully serviceable, i.e. the DPs must be read correctly and the meter body must be free of any performance affecting problems.

When a DP meter system is physically fully serviceable and that meters performance criteria and geometry is correctly entered into the calculations, the expected and found meter performance will overlap and agree. Only when the found and expected meter performances agree within allowable uncertainties does the diagnostic system give the meter a 'clean bill of health'.

If ***either*** (or both) of these two conditions are not met then the DP meter will mis-measure the flow rate. Prognosis monitors for *both* these flow rate prediction bias producing scenarios. The diagnostic system **is not** dependent on the correctness of the expected (i.e. calibrated) performance criteria. The diagnostic system uses:

- the expected performance to judge the correctness of the found performance, **<u>and</u>**
- the found performance to judge the correctness of the expected performance!

Prognosis **does not** contain any inherent unproven assumption where the expected meter performance criteria are fixed 'trusted' values with which the 'questionable' found meter performance must overlap. On the contrary, the diagnostic system treats both the expected and found meter performance as equally questionable until it is shown that the expected and found meter performances agree with each other.

- If the DP meter system <u>is</u> physically serviceable, and that meters performance criteria and geometry are <u>correctly</u> entered, then the expected and found meter performances <u>will</u> agree, and the diagnostics correctly gives no alarm.
- If the meter <u>is not</u> physically serviceable, and the serviceable meters performance criteria and geometry are <u>correctly</u> entered, then the expected and found meter performance <u>will not</u> agree, and the diagnostics correctly gives an alarm.
- If the meter <u>is</u> physically serviceable, and the meters performance criteria and geometry are <u>incorrectly</u> entered, then the expected and found meter performance <u>will not</u> agree, and the diagnostics correctly gives an alarm.
- If the meter <u>is not</u> physically serviceable, and the meters performance criteria and geometry are <u>incorrectly</u> entered, then the expected and found meter performance <u>will not</u> agree (expect in the ***extremely*** unlikely and freakish coincidence where the two independent problems would need to combine to neutralize all seven different diagnostic checks), and the diagnostics correctly gives an alarm.

Therefore, only when the questionable 'found' DP meter performance and the equally questionable 'expected' DP meter performance agree with each other (within allowable uncertainties) is it shown that the meter system is serviceable and the flow rate prediction is trustworthy. Either scenario of an erroneous expected performance or an unserviceable meter system (or both together) will trigger Prognosis to correctly produce a warning that the flow rate prediction is untrustworthy.

4. Disturbed Flow Cone Meter Performance Tests & Results

In 2009 DP Diagnostics tested a 4”, sch 80, 0.63β cone meter (with a downstream pressure tap) with straight pipe runs and then disturbances. Calibrating the meter for diagnostics took no more effort or expense than a standard calibration. The meter is shown in Figures 5 thru 12. In order to put the 2012 COP 4”, sch 80, 0.75β cone meter flow test results in context this earlier 2009 test series will be discussed first.

4a. DP Diagnostics 2009 4”, sch 80, 0.63β Cone Meter Tests

To appreciate the position of the cone to the exit of the component generating flow disturbances, the upstream pressure port is 1.5D downstream of the meters inlet flange face and 2.125” (≈ 0.5D) upstream of the cone apex. Thus a distance of ‘0D’ corresponds to the exit of the disturbance generating device being 2D upstream of the cone. Cone meter manufacturers can (and do) vary the position of the cone within the meter body thus producing some straight length pipe run while on paper it can look like there is none.

The straight pipe run (‘baseline’) calibration set up is shown in Figure 5. The resulting calibration parameters were checked against a variety of typical real world installations. Figures 6 thru 12 show the various flow disturbance tests conducted on this meter, i.e.:

Figure 6: Double Out of Plane Bend (‘DOPB’) at 0D upstream.
Figure 7: DOPB at 0D upstream with Half Moon Plate (‘HMP’) at 2D downstream.
Figure 8. DOPB at 0D upstream & Triple Out of Plane (TOPB) downstream.
Figure 9. HMP 6.7D upstream.
Figure 10. HMP 8.7D upstream.
Figure 11. HMP 2D downstream.
Figure 12. 3”(54^0) Swirl Generator upstream of an 4” Pipe 9D Expansion upstream.

The DOPB test (Figure 6) was also conducted at 2D & 5D (not shown). The half moon orifice plate (HMP) blocked the top half of the cross sectional area and models a gate valve at 50% closed. A real gate valve has the gate centered on the valve seat with flanges at either side to connect it to the pipe system. Thus typically the gate is 1.5D to 2D from the adjacent flange. The HMP sandwiched between two flanges was given 2D on either side of the plate to mimic a gate valve installation at 0D. As such the upstream HMP installed at 6.7D and 8.7 D upstream models a gate valve 50% closed at approximately 5D and 7D upstream of the cone meter inlet flange. The downstream HMP installed at 2D (Fig. 11) models a gate valve 50% closed at approximately 0D downstream of the cone meter. (There is 3D between the cone and the meter exit.)

Cone meters require individual calibration, as discussed by Hodges et al [7]. The baseline calibration results are shown in Figures 13 & 14 along with the data fit uncertainties. The baseline tests were carried out at two pressures (17 & 41 Bar). The sonic nozzle reference had a 0.35% uncertainty and 0.1% repeatability. Figure 13 shows the baseline flow coefficients. A constant discharge coefficient gave an uncertainty

Figure 5: Baseline Installation

Figure 6: DOPB, 0D up

Figure 7: DOPB 0D up & HMP 2D down

Figure 8: DOPB 0D up & TOPB down

Figure 9: HMP 6.7D up

Figure10: HMP 8.7D up

of 0.5%. The expansion and PPL flow coefficient linear Reynolds number fits both give 1.1% uncertainty. Figure 14 shows that the DP ratios, the constant value data fits and associated uncertainties.

Due to the extensive testing, and the fact that that pressure does not affect the parameters, all flow disturbance tests were carried out at one nominal pressure of 17 Bara. Figures 15, 16 & 17 show the calibrated discharge, expansion & PPL flow coefficients across all the subsequent disturbances tested. Figure 15 shows that this cone meter is extremely

Figure 11: HMP 2D down

Figure 12: 3" Swirl Generator+9D up Exp

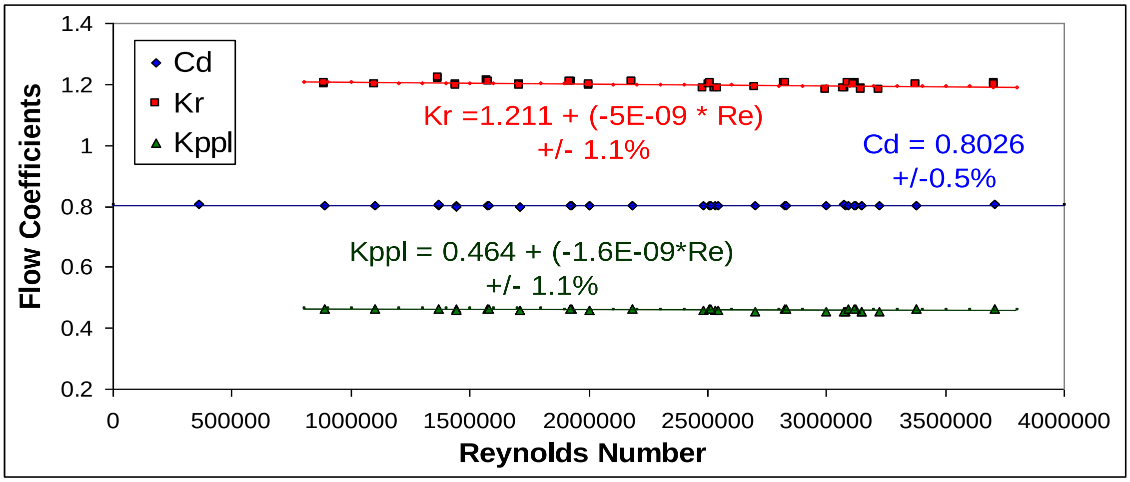

Figure 13: 4", 0.63β cone meter baseline flow coefficient results.

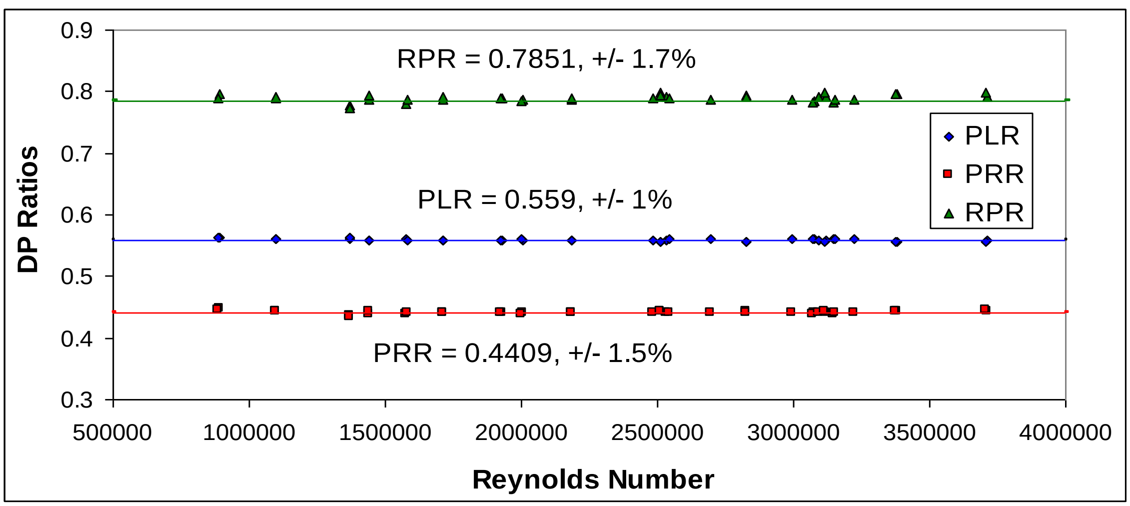

Figure 14: 4", 0.63β cone meter baseline DP ratio results.

resistant to disturbed flow. Only two installations caused the predicted discharge coefficient to vary beyond the baseline 0.5% uncertainty, i.e. the HMP upstream installations and the swirl generator with expander upstream installation. Both installations are extreme, and rare in the real world.

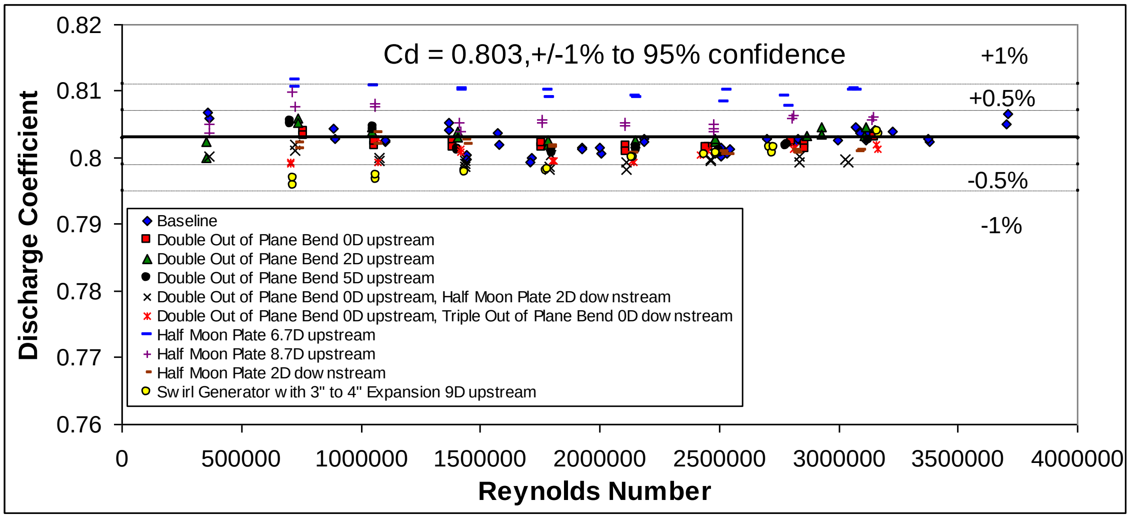

Figure 15: 4”, 0.63β cone meter disturbed flow discharge coefficient results.

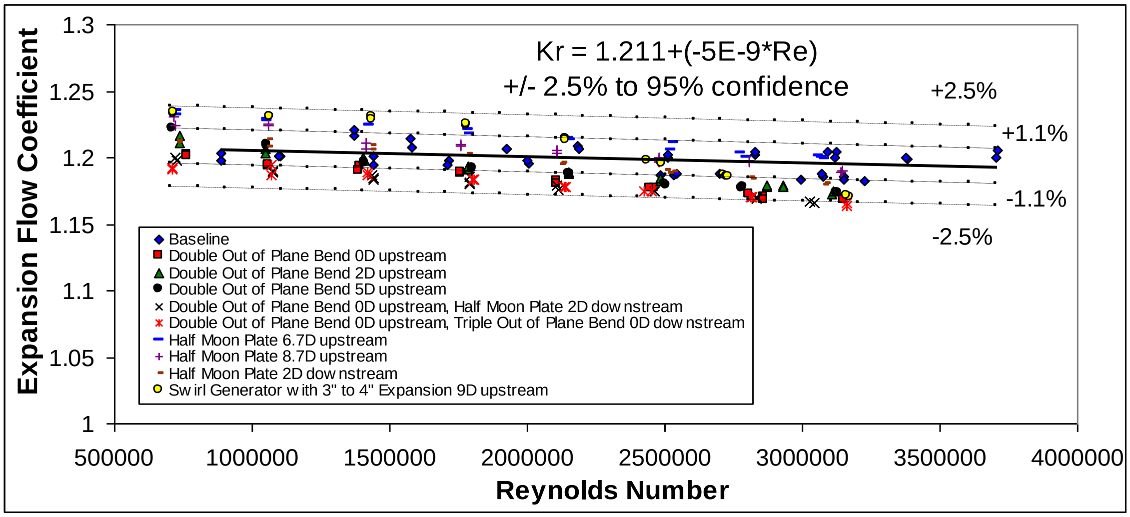

Figure 16: 4”, 0.63β cone meter disturbed flow expansion coefficient results.

The HMP at 6.7D, i.e. gate valve at 5D upstream is a short upstream distance for such an extreme disturbance. This disturbance produced a slight discharge coefficient bias averaging +0.8%. By 8.7D, i.e. a gate valve at 7D upstream, the meter performance was within the baseline calibration uncertainty (when allowing for reference meter repeatability and 95% confidence in the data).

The extreme swirl with a 9D expansion upstream is an extreme disturbance. This disturbance produced a slight discharge coefficient bias averaging -0.6 % which deteriorated to -1% at low flow.

Figures 16 & 17 show the disturbance effects on the expansion and PPL flow coefficients. These parameters’ resistance to disturbed flow is critical to the practical applicability of the diagnostic methodology for cone meters. The disturbed flow has a greater adverse effect on both these coefficients than it does on the discharge coefficient, but, crucially they are also both ***relatively*** immune to the disturbances in the flow. The

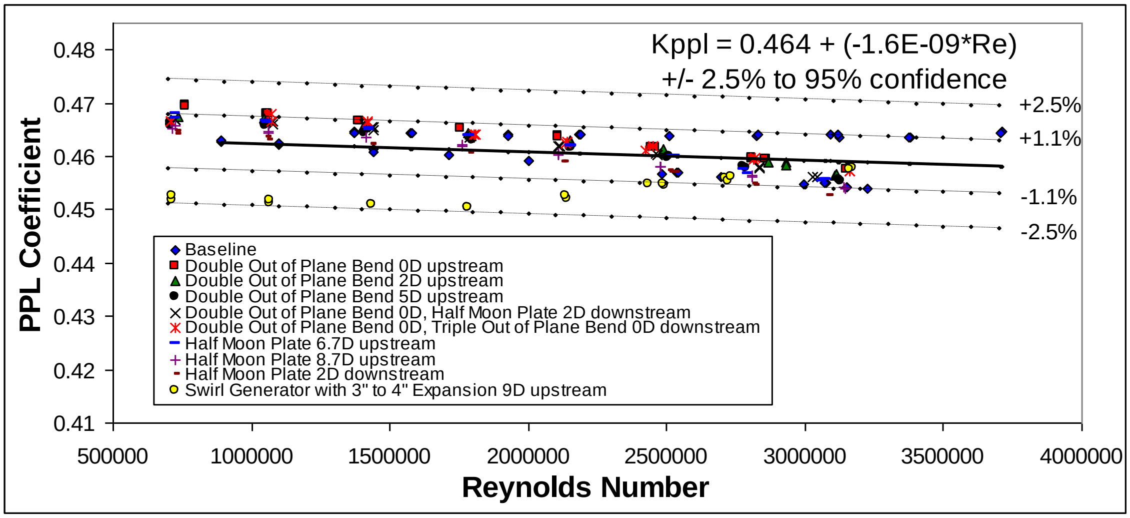

Figure 17: 4", 0.63β cone meter disturbed flow PPL coefficient results.

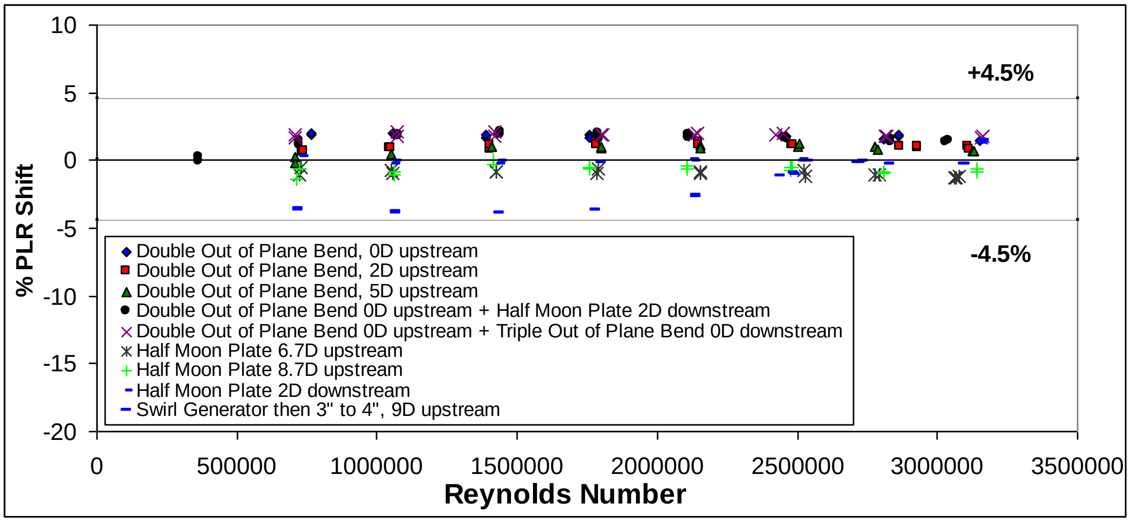

Figure 18: 4", 0.63β cone meter disturbed flow PLR results.

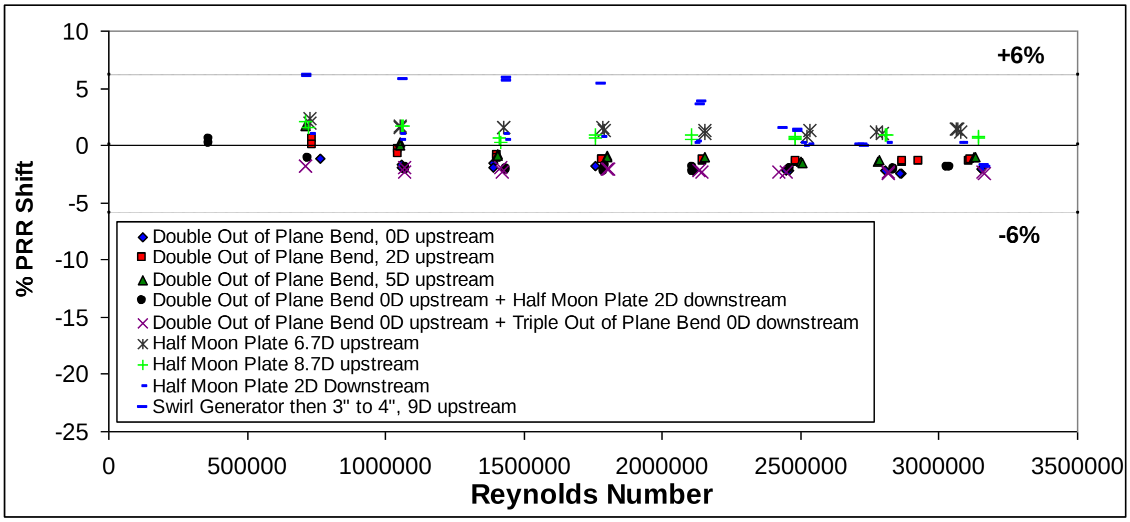

Figure 19: 4", 0.63β cone meter disturbed flow PRR results.

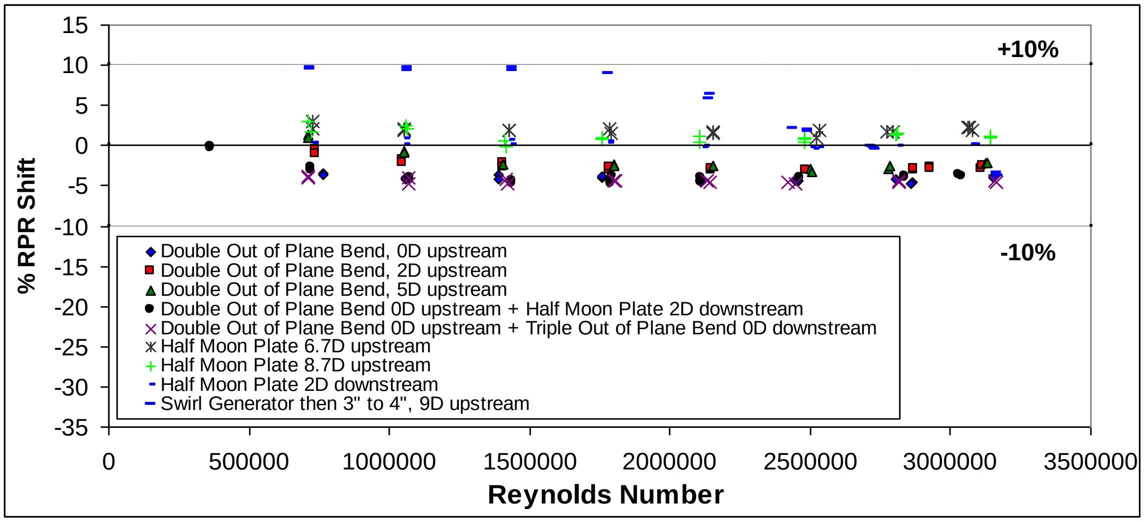

Figure 20: 4", 0.63β cone meter disturbed flow RPR results.

different disturbances cause the spread of data around both the expansion & PPL coefficients baseline data fits to increase from ±1.1% to ±2.5%.

Figures 18, 19 & 20 show the PLR, PRR & RPR respectively, across all the disturbances tested. The DP ratio uncertainty increase due to the disturbances was significantly larger than for the flow coefficients. The PLR uncertainty was increased to 4.5%, the PRR uncertainty was increased to 6%, and the RPR uncertainty was increased to 10%. However, it is clear that much of this increase is solely due to the extreme case of the swirl generator with the expander 9D upstream. It could look like these large DP ratio uncertainty increases could adversely affect the practicality of Prognosis. However, it will be shown in Section 4 that the DP ratios can be so greatly affected by common cone meter malfunctions that these uncertainty limits are still very much of practical use.

When assigning diagnostic parameter uncertainties, as the cone meters are likely to be exposed to disturbed flow, it is prudent to expand the uncertainties to account for disturbed flow. Therefore, the prudent 4", 0.63β cone meter parameter uncertainties are:

$C_d = 0.803$, ±1% (i.e. ±x%)	PLR = 0.5591, ±4.5% (i.e. ±a%)
$K_r = 1.211 + (-5E-9*\text{Re})$, ±2.5% (i.e. ±y%)	PRR = 0.4409, ±6.0% (i.e. ±b%)
$K_{PPL} = 0.464 + (-1.6E-9*\text{Re})$, ±2.5% (i.e. ±z%)	RPR = 0.7851, ±10.0% (i.e. ±c%)

Traditional & PPL Meters max % rms $\quad \phi\% = \sqrt{(\pm 1\%)^2 + (\pm 2.5\%)^2} = \pm 2.7\%$

Traditional & Expansion Meters max % rms $\quad \xi\% = \sqrt{(\pm 1\%)^2 + (\pm 2.5\%)^2} = \pm 2.7\%$

Expansion & PPL Meters max % rms, $\quad \upsilon\% = \sqrt{(\pm 2.5\%)^2 + (\pm 2.5\%)^2} = \pm 3.5\%$

Expanded calibration uncertainties allows Prognosis to account for real world installation effects, thereby avoiding false alarms triggered by disturbed flows when the cone meters primary flow rate prediction is still operating within the assigned uncertainty. This is of help in current oil field operations – as excessive - false alarms – are nuisance alarms – mitigating the Prognosis use in operations.

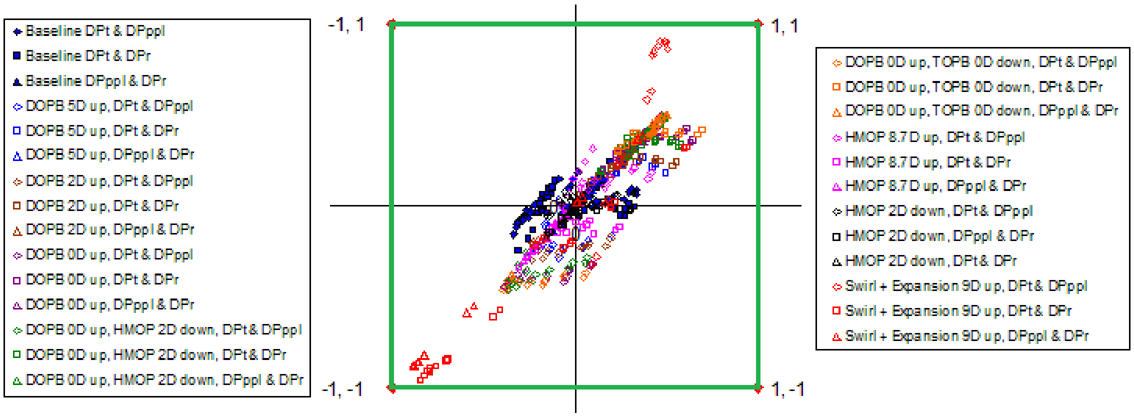

Figure 21: NDB for all data recorded from 4”, 0.63β cone meter.

Figure 21 shows the 2009 4”, 0.63β cone meter data (with expanded uncertainties) plotted on the diagnostic NDB graph. The DP summation test, i.e. (x_4 , 0), is absent from Figure 21 as it was added to the graphical display in 2010. (During all these tests the equation 1 DP check held true as required.) Figure 21 looks cluttered, but this is due to multiple test data being superimposed on the NDB. In practice there are only four points shown at any one time making the diagnostic result clear (e.g. see Figure 4).

4b. <u>COP 2012 4”, sch 80, 0.75β Cone Meter Tests</u>

In 2012 COP tested the 4”, sch 80, 0.75β cone meter at CEESI to investigate a higher beta ratio cone meters level of resistance to flow disturbances. COP does not advocate cone meter beta ratios exceeding 0.75. The meter installations are shown in Figures 22 thru 28. Again, the upstream pressure port is 1.5D downstream of the meters inlet flange face and 2.125” (≈ 0.5D) upstream of the cone apex. Therefore, a distance of ‘0D’ corresponds to the disturbance device outlet being 2D upstream of the cone. Figure 22 shows the baseline calibration installation. The meter was then tested with the COP chosen following installations:

Figures 23 & 24: 90^0 bend at 5D and 0D upstream respectively
Figure 25: Double out of plane bend (DOPB) 0D upstream
Figure 26: 3” to 4” expansion at 2D upstream
Figure 27: HMP at 5D upstream
Figure 28: 3” swirl generator upstream of a 3” to 4” expansion at 9D upstream.

The reference meter was a sonic nozzle with an uncertainty of 0.35% and a repeatability of 0.1%. The baseline results, conducted at 20 Bara for the calibration parameters are shown in Figures 29 & 30 with the data fit uncertainties. Figure 29 shows the flow coefficients. A constant discharge coefficient was fitted to 0.5% uncertainty. Although the expansion and PPL flow coefficients here could be fitted to the Reynolds number (to the same 1.1% uncertainty as the 0.63β cone meter) constant value fits were chosen, at 1.5% uncertainty for the expansion flow coefficient and 2% uncertainty for the PPL flow coefficient. Figure 30 shows that the DP ratios, the constant value data fits and associated uncertainties. The DP ratio uncertainties are similar to the 4", 0.63 beta ratio cone meter (see Figure 14).

Figure 22. COP 4", 0.75β cone meter straight pipe run (baseline) installation.

Figure 23: 90^0 bend at 5D upstream

Figure 24: 90^0 bend at 0D upstream

Figure 25: DOPB 0D upstream

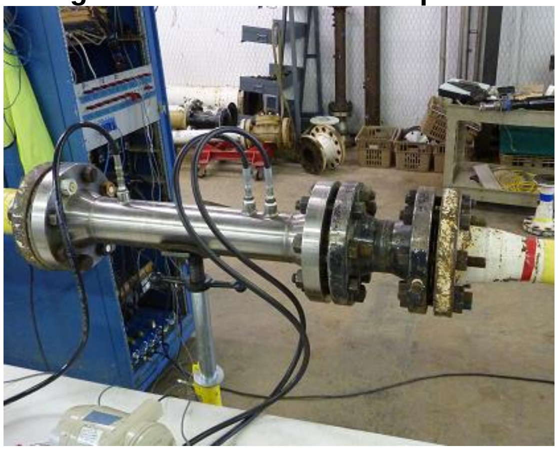

Figure 26: 3" to 4" at 2D Upstream

Figure 27: HMP 5D upstream

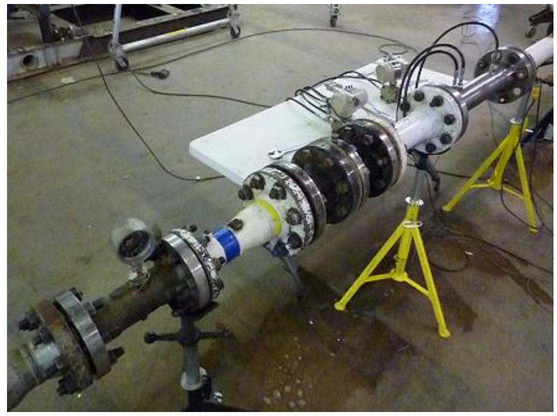

Figure 28: 3" Swirl Generator+9D up Exp

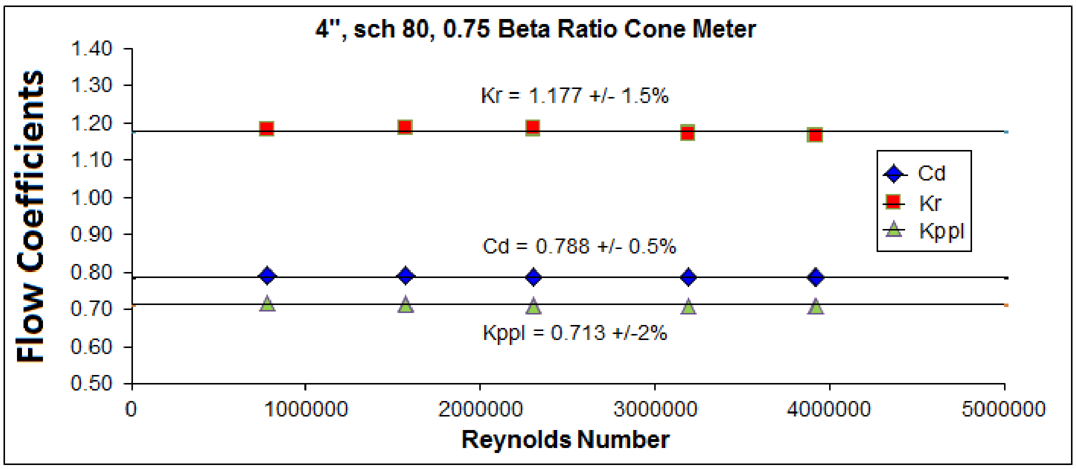

Figure 29. 4", 0.75β cone meter baseline flow coefficient results.

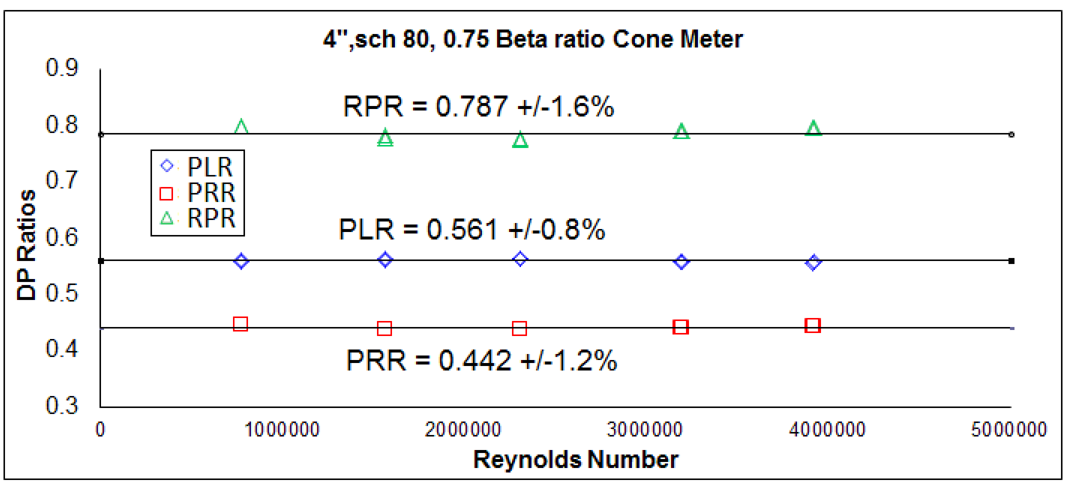

Figure 30. 4", 0.75β cone meter baseline DP ratio results.

All flow disturbance tests were conducted at 20 Bara. Figures 31, 32 & 33 show the calibrated discharge, expansion & PPL flow coefficients across the disturbance tests. Figure 31 shows that this cone meter is very resistant to disturbed flow. Only two installations caused the predicted discharge coefficient to vary beyond the baseline ±0.5% uncertainty (except marginally at the very lowest flow rate only). This is the 90^0 bend at

0D upstream installation and the swirl generator with expander 9D upstream installation. Both installations are extreme. The first installation is a relatively common suggestion for applications with limited straight pipe run, while the second is a very rare scenario in the real world. The discharge coefficient for the 90^0 bend at 0D upstream is marginally out-with the 1% uncertainty at the lowest flow rate tested. The swirl generator with expander 9D upstream produces a very significant shift in meter performance.

Figure 31 shows that the 4", 0.75β cone meter with a single 90^0 bend at 5D had the same performance as the baseline calibration. It therefore appears prudent to supply some straight length pipe between a single 90^0 bend and a 0.75β cone meter.

It may seem surprising that the meter is immune to a DOPB at 0D but not a single bend at 0D. A DOPB is often perceived as a more extreme disturbance. However, a single 90^0 bend and a DOPB do not produce the same type of flow disturbance. A DOPB does not produce a more extreme version of the disturbance induced by a single 90^0 bend. A DOPB and a single bend produce different levels of asymmetric flow and swirl.

Figure 31 shows that the 0.75β meter is adversely affected by the swirl generator with expander 9D upstream. This is the one significant difference between the two different beta ratio cone meter test results. The 0.75β cone meter is not affected by the expansion at 2D upstream. Therefore, the *extreme* swirl appears to be the issue. Whereas the DOPB produces moderate and realistic swirl, the swirl generator's 54^0 of swirl is far more extreme than the vast majority of real world applications. It is therefore suggested here that these results should be taken in context and not dwelled upon unduly. It appears that a cone meter, like all flow meters, should not be used with *very* severe swirl flows.

It was found from the single test conducted that the 0.75β cone meter seems slightly more resistant to the HMP than the 0.63β cone meter. A HMP 5D (i.e. gate valve at 3D) upstream appears to have no significant adverse effect on the 0.75β cone meter. It took the 0.63β cone meter an upstream distance from the HMP of 8.7D (i.e. a gate valve at 7D) for there to be no significant adverse effect. There isn't enough repeat data to make any defensible conclusions. However, it would be prudent to allow at least 7D between a gate valve and a cone meter.

Figures 32 & 33 show the disturbance effects on the expansion and PPL flow coefficients. As with the 0.63β cone meter, both parameters are more affected than the discharge coefficient, but, crucially they are also both ***relatively*** immune to the disturbances in the flow. The only major shift of flow coefficients is from the extreme test of the swirl generator with expander 9D upstream. Ignoring this unrealistic test to concentrate on the more realistic real world examples, the different disturbances cause the spread of data around the expansion coefficient baseline data fit to increase from 1.5% to 3.0%, while the PPL coefficient uncertainty remains at 2.0%.

Figures 34, 35 & 36 show the PLR, PRR & RPR respectively, across all the 0.75β cone meter extreme disturbances tested. Ignoring the unrealistic swirl generator with expander 9D upstream tests it can be seen that the flow disturbances impose a moderate increase in the DP ratio uncertainties. The PLR and PRR uncertainties can be set to 3%, and the RPR set to 6% uncertainty.

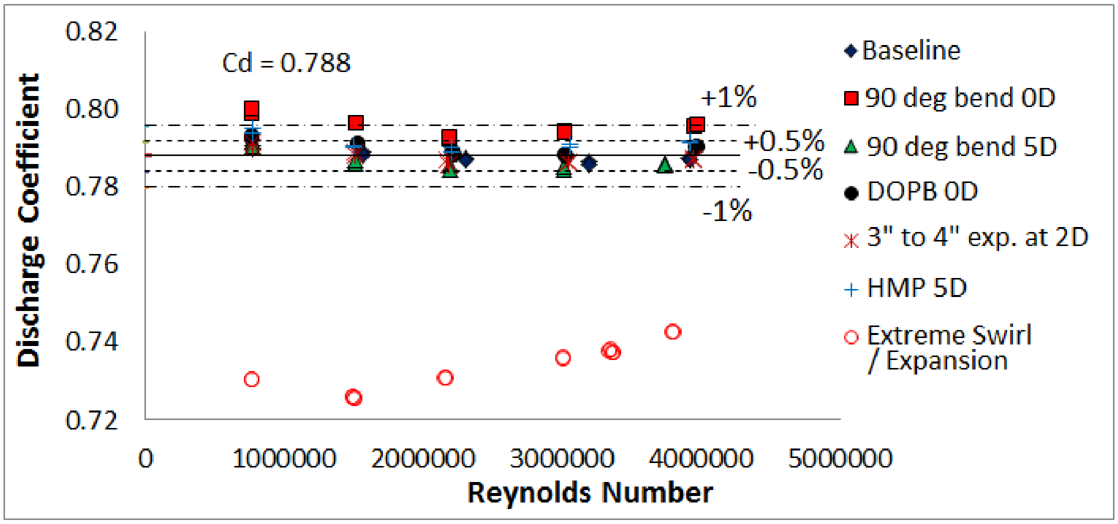

Figure 31: 4", 0.75β cone meter disturbed flow discharge coefficient results.

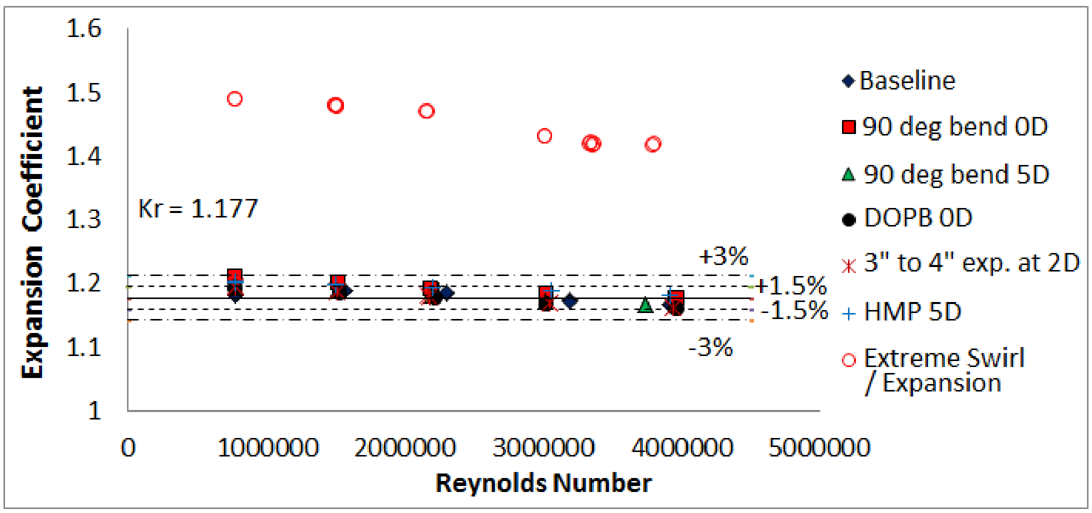

Figure 32: 4", 0.75β cone meter disturbed flow expansion coefficient results.

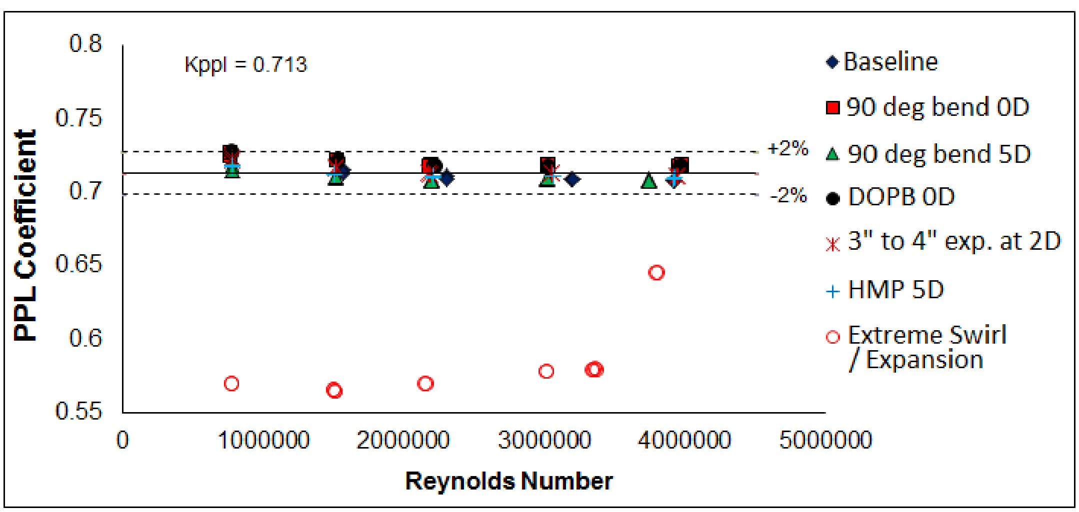

Figure 33. 4", 0.75β cone meter disturbed flow PPL coefficient results

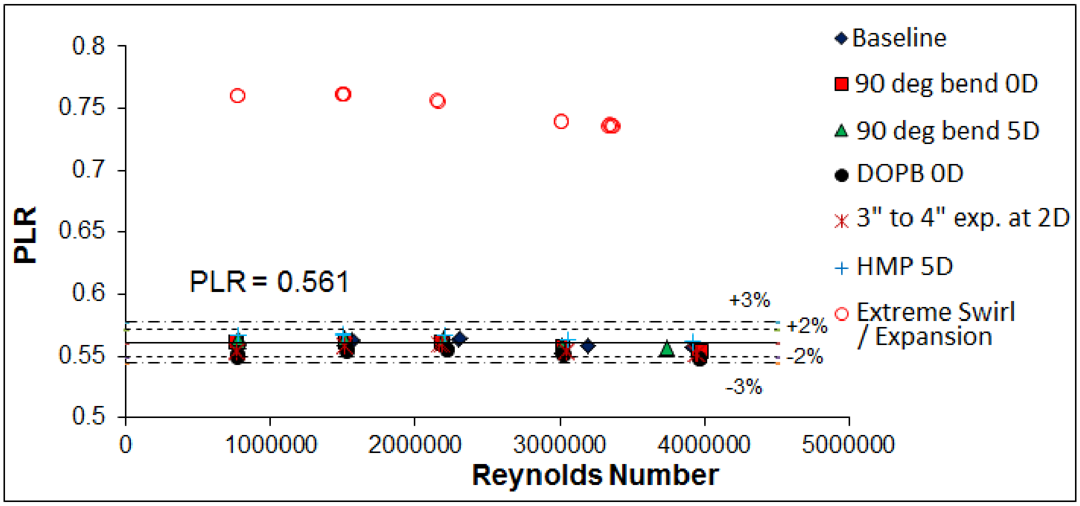

Figure 34. 4”, 0.75β cone meter disturbed flow PLR results.

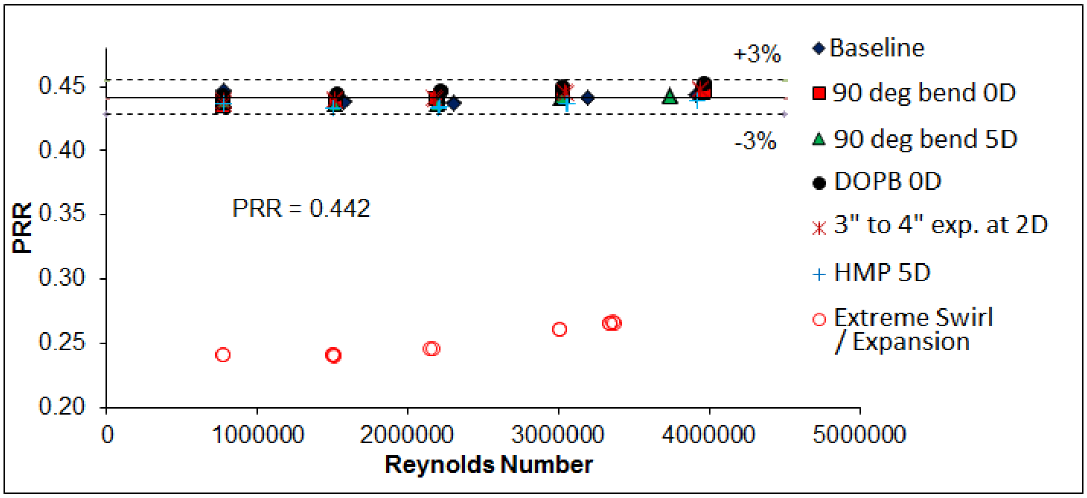

Figure 35. 4”, 0.63β cone meter disturbed flow PRR results.

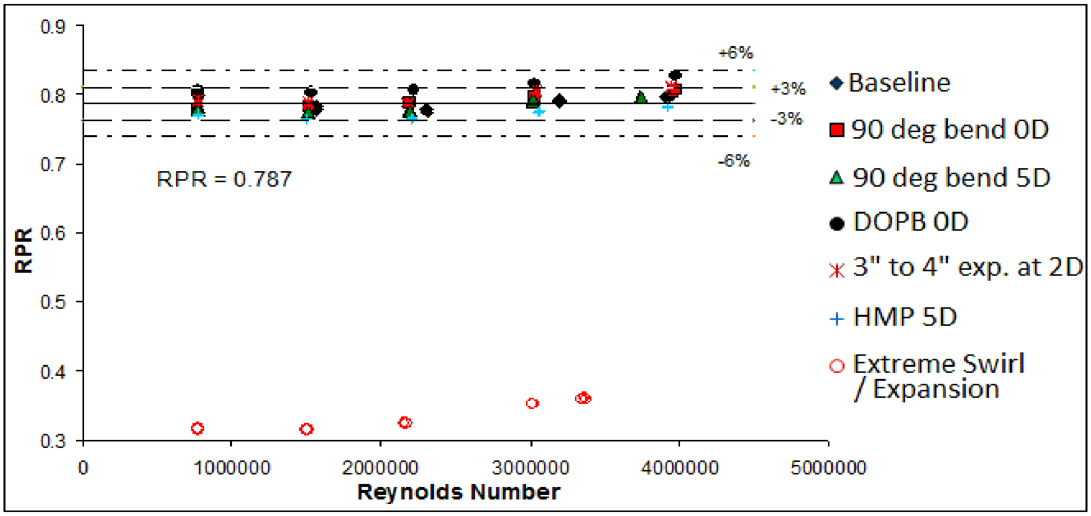

Figure 36. 4”, 0.63β cone meter disturbed flow RPR results.

It is worth noting that when the unrealistic swirl generator with expander 9D upstream test data sets are removed, the two different beta ratio cone meters have very similar diagnostic parameter uncertainties. The 4", sch 80, 0.75 beta ratio calibration results for the diagnostic system are:

$C_d = 0.788$, ±1% (i.e. ±x%) PLR = 0.561, ±3% (i.e. ±a%)
$K_r = 1.177$, ±3% (i.e. ±y%) PRR = 0.442, ±3% (i.e. ±b%)
$K_{PPL} = 0.713$, ±2% (i.e. ±z%) RPR = 0.787, ±6% (i.e. ±c%)

Traditional & PPL Meters max % rms $\phi\% = \sqrt{(\pm 1\%)^2 + (\pm 2\%)^2} = \pm\ 2.3\%$

Traditional & Expansion Meters max % rms $\xi\% = \sqrt{(\pm 1\%)^2 + (\pm 3\%)^2} = \pm\ 3.2\%$

Expansion & PPL Meters max % rms, $\upsilon\% = \sqrt{(\pm 2\%)^2 + (\pm 3\%)^2} = \pm\ 3.6\%$

Figure 37 shows, the diagnostic results when using these uncertainties with sample data (i.e. the highest flow rates) for each flow test configuration.

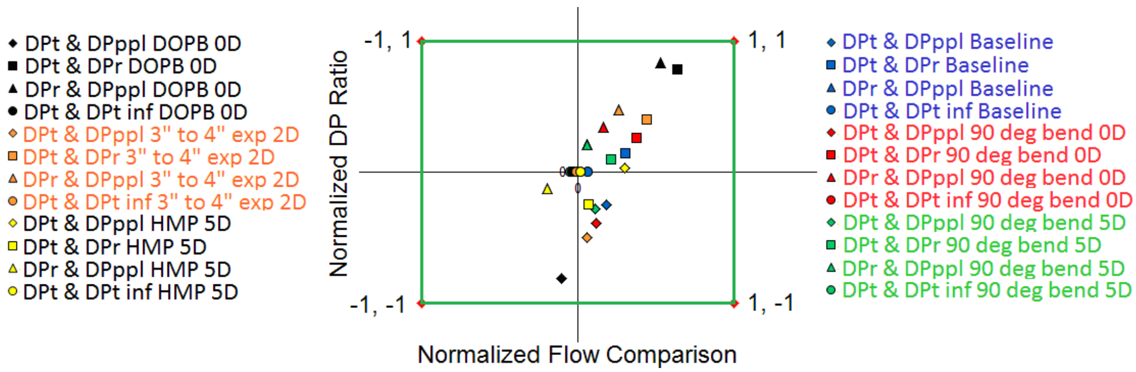

Figure 37. NDB for all disturbed flow recorded from 4", 0.75β cone meter (except the 54^0 swirl upstream of a 3" to 4" expansion).

Future cone meters could be calibrated with straight pipe inlets to determine baseline flow parameters, and then larger diagnostic parameter uncertainties can be applied if the meter is to be in service with disturbed flow. This practice minimizes the chance of disturbed flows which are metered correctly causing false alarms.

5. Cone Meter Performance in Abnormal Operating Conditions

Flow meters may encounter various problems during service. Using either the 4", 0.63β or 0.75β cone meter test results the following section gives a few examples of the diagnostics in operation.

5a. Flow Rate Prediction Bias Due to Extremely Disturbed Flow

The flow disturbance of the swirl generator and expansion 9D upstream of the 4", 0.75β cone meter (see Figure 38) was so extreme it induced a significant flow rate bias of +7.8%. Traditionally, there is no accepted method for a DP meter to self-diagnose it has a problem. However, with this meter's diagnostic parameter uncertainties set to the expanded values discussed in page 21, and the standard DP summation uncertainty of 1%

used, Figure 38 shows Prognosis warning the operator that there is a flow meter problem. A mid-Reynolds number of 2.17e6 is used in this example. The DP check shows the DP readings trustworthy indicating that the problem lies with the performance of the meter body. In this case, the flow disturbance is skewing the meter's performance. This is an example of the 'found' meter performance being the problem when compared to the 'expected' performance.

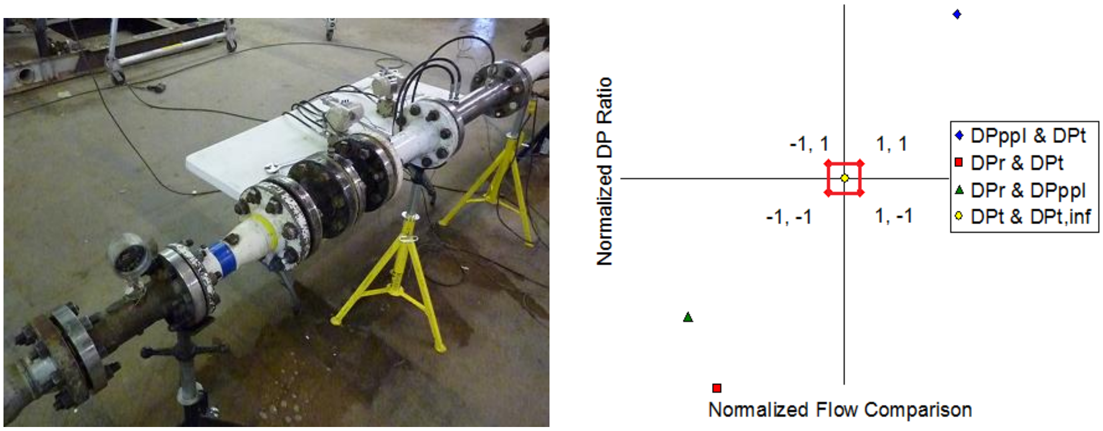

Figure 38. 4", 0.75β cone meter with extreme flow disturbance & diagnostic result.

5b. <u>Cone Meter Performance with a Partially Blocked Minimum Flow Area</u>

DP meter primary elements are intrusive to the flow. The cone element can act as a trap to debris, which will cause flow metering errors. Figure 39 shows a partial blockage with a small nut trapped by the 4", 0.63 beta ratio cone. For realism, this blockage was applied when the meter was installed in a typically challenging cone meter application, i.e. a DOPB at 0D upstream and a HMP installed 2D downstream (see Figure 7). The flow rate prediction recorded a +5% bias induced by the trapped nut. Traditionally, there is no accepted method for a DP meter to self-diagnose it has a problem.

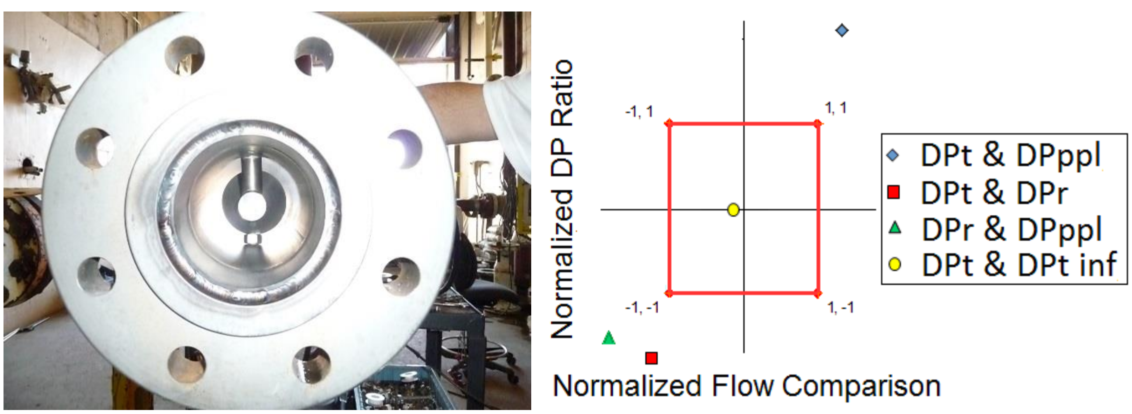

Figure 39: Trapped nut looking downstream & NDB diagnostic result.

Figure 39 also shows the diagnostic result for the trapped nut in this installation. The data for a mid-range flow rate is shown. The expanded diagnostic uncertainties shown in page 14 were used, plus the standard DP summation uncertainty of 1%. When the meter had no malfunction, there was no diagnostic warning (see Figure 21), but with the trapped nut causing a +5% bias the diagnostics clearly indicated a malfunction. This is an example of the 'found' meter system performance being the problem when compared to the 'expected' meter performance.

5c. <u>DP Transmitter Problems</u>

DP transmitters can malfunction for various reasons, including being over-ranged (i.e. 'saturated'), drifting, or being incorrectly calibrated. An erroneous traditional DP measurement means an erroneous flow rate prediction. Traditionally, there is no accepted method for a DP meter to diagnose it has a DP reading problem.

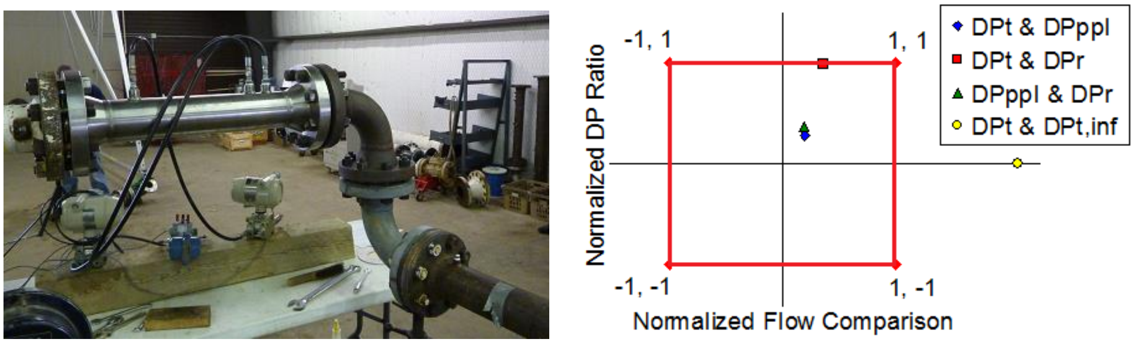

Figure 40: 4", 0.75β cone meter DOPB 0D upstream with DP saturation.

In this example, for realism regards typical cone meter installations, take the 4", 0.75β cone meter installed with a DOPB at 0D (see Figures 25 & 40). At 20 Bar, the air flow Reynolds number of 22.2e6 produced a correctly measured traditional DP of 51.06"WC (12,696 Pa), the meter predicted the correct flow rate to within 0.5%, and the diagnostic system correctly indicated no problem existed.

As an example, consider what would have happened if the DP transmitter became saturated at 50"WC (12,432 Pa). The DP error is approximately -2% and the corresponding flow rate error is -1%. Figure 40 shows the diagnostic result. The diagnostic parameter uncertainties used were those stated in page 21, plus the standard DP summation uncertainty of 1%. Prognosis correctly shows a system malfunction. The DP check diagnostic shows that the problem is with a DP reading by the fact that the DP reading warning is given.

5d.1. <u>Incorrect Geometry Inputs – Inlet Diameter</u>

Incorrect geometry keypad entries are a relatively common problem. They produce flow rate prediction biases. This scenario is an example of the metering systems hardware as 'found' operating correctly, whereas the 'expected' performance of the meter is erroneous, as the flow computer calculation expects the performance of a different geometry meter.

As cone meters are not *always* used in 'tight spaces' with disturbed flow at the inlet, consider a Reynolds number 3.15e6 in the 4", 0.63β cone meter straight pipe run calibration (i.e. Figure 22). The true inlet diameter of this meter is 3.826". However, if an incorrect keypad entry of the inlet diameter is used - the inlet diameter of a 4", sch 40, i.e. 4.026" - a positive flow rate prediction bias of 24.6% is induced. Figure 21 included this test data with the correct geometry entered. Figure 41 now shows the same data when this wrong inlet diameter is entered. The diagnostic parameter uncertainties used were those stated in page 14, plus the standard DP summation uncertainty of 1%. The diagnostics indicate a problem. The DP check shows the DP readings are trustworthy and hence, the problem is with the meter body (which is correct as the expected and found meter geometries are different).

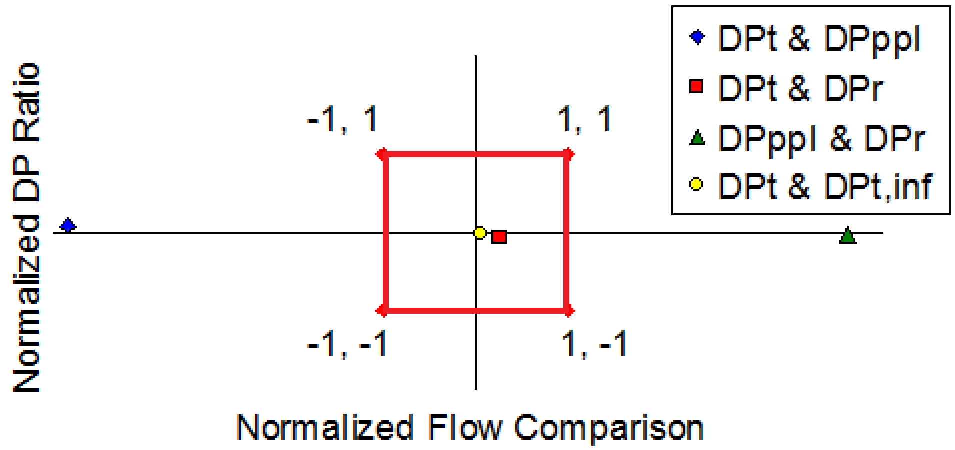

Figure 41. 4", sch 80, 0.63β cone meter with incorrectly entered sch 40 inlet diameter value.

The 4", 0.63β cone meter flow rate prediction bias of +24.6% induced by the use of this +5.23% incorrect diameter could be surprising to many engineers. A 4", 0.63β Venturi, nozzle or orifice meter with a +5.23% incorrect diameter input has a -1.7% flow rate prediction bias. The cone meters prediction bias is in the opposite direction and a different order of magnitude. The reason the cone meter is far more sensitive to inlet diameter biases is due to the difference in geometry between a cone meter and these other DP meters, combined with how the respective geometry values are used in the flow rate calculation.

Venturi, nozzle & orifice meter geometry is described via the inlet (D) and throat diameter (d), i.e. by <u>the size of the inlet and throat **flow** diameters</u>. From this information these DP meter designs product of velocity of approach (E) and throat area (A_t) is calculated in the DP meter traditional flow rate equation (i.e. equation 2), as shown in equation 2a. However, cone meter geometry is described via the inlet diameter (D) and ***cone*** diameter (d_c), i.e. by <u>the size of the inlet flow diameter and the cone **blockage** diameter</u>. From this subtly different information the cone meters product of velocity of approach (E) and throat area (A_t) is calculated in the DP meter traditional flow rate equation as shown in equation 2b.

A consequence of this is that whereas with Venturi, nozzle & orifice meter geometries the flow rate prediction is relatively insensitive to the inlet diameter, the cone meter flow rate prediction is **very sensitive to the inlet diameter**. Figure 42 shows the percentage flow rate prediction biases induced on Venturi, nozzle & orifice meter flow rate predictions, and then on a cone meter flow rate predictions, for percentage diameter biases. Note that this relationship is beta ratio dependent – Figure 42 is only applicable to this particular 0.63 beta ratio example.

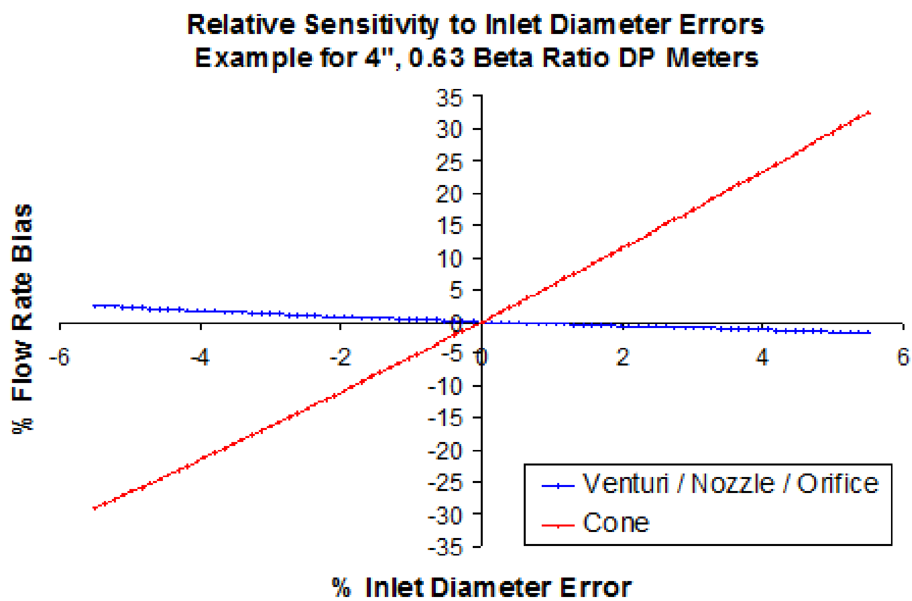

Figure 42. Relative Sensitivity of 4", 0.63β DP Meter Designs to Inlet Diameter Biases.

Venturi, orifice meter: $$\dot{m} = EA_t \varepsilon C_d \sqrt{2\rho\Delta P_t} = \left\{ \frac{\pi}{4} \left(\frac{d^2}{\sqrt{1-\left(\frac{d}{D}\right)^4}} \right) \right\} \varepsilon C_d \sqrt{2\rho\Delta P_t} \qquad \text{--- (2a)}$$

Cone meter: $$\dot{m} = EA_t \varepsilon C_d \sqrt{2\rho\Delta P_t} = \left\{ \frac{\pi}{4} \left(\frac{\left(D^2 - d_c^2\right)}{\sqrt{1-\left\{\sqrt{1-\left(\frac{d_c}{D}\right)^2}\right\}^4}} \right) \right\} \varepsilon C_d \sqrt{2\rho\Delta P_t} \qquad \text{--- (2b)}$$

It is far more critical that a cone meter operator keypad enters the precise cone meter inlet diameter than it is for Venturi, nozzle & orifice meter dimensional keypad entries. Surprisingly few operators of cone meters know this. However, Prognosis is capable of automatically monitoring this issue for the operator (see Figure 41).

5d.2. <u>Incorrect Geometry Inputs – Incorrect Cone Diameter</u>

Cone (and all DP) meters are dependent on the throat area (A_t) being correctly entered into the flow calculation software. In the case of a cone meter this means the correct keypad entry of both the inlet diameter (D) and cone diameter (d_c). For Venturi, nozzle and orifice meters this means the correct keypad entry of only the throat diameter (d). Let us now consider the effect of an incorrect cone diameter input.

The actual cone diameter of the 4", sch 80, 0.63β cone meter is 2.998". If. say, the cone diameter was erroneously entered as 2.898" (i.e. a -3.3% cone diameter error) the induced flow rate prediction bias is +11.9%. This scenario is another example of the metering systems hardware as 'found' operating correctly, whereas the 'expected' performance of the meter is erroneous, as the flow computer calculation expects the performance of a different geometry meter.

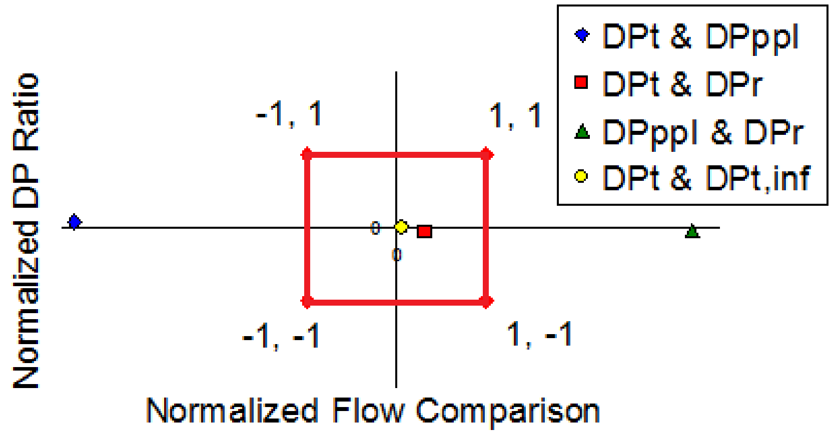

Figure 43: 4", 0.63 beta ratio cone meter with a high cone diameter of 2.631".

Figure 43 show the diagnostic result for the Reynolds number 3.15e6 flow point discussed in Section 5d.1. The diagnostic parameter uncertainties used were stated in page 14, plus the standard DP summation uncertainty of 1%. The diagnostics indicate a problem. The DP check shows the DP readings trustworthy indicating that the problem lies with the performance of the meter body (which is correct as the expected and found meter geometries are different).

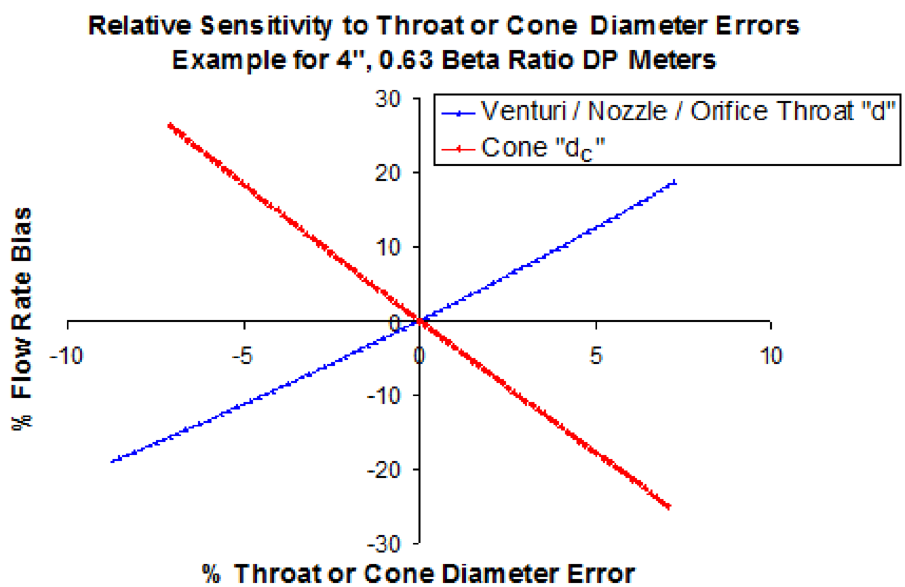

Figure 44. Relative Sensitivity of 4", 0.63β DP Meter Designs to Throat Diameter Biases.

For completeness, Figure 44 shows the percentage flow rate prediction biases induced on Venturi, nozzle & orifice meter flow rate predictions, and the cone meter flow rate predictions, for their respective throat or cone diameter input percentage biases. As with the inlet diameter case this relationship is beta ratio dependent and hence Figure 44 is only applicable to the 0.63 beta ratio example. In this case both the cone and the other DP meter designs are particularly sensitive to this issue, with the cone meter being marginally more sensitive.

5e Incorrect Cone Meter Performance Parameter Keypad Entry

It is not just geometry entries that can be erroneous. Performance parameters such as the discharge coefficient can be keypad entered incorrectly. This is another example of the metering systems hardware as 'found' operating correctly, whereas the 'expected' performance of the meter is erroneous, as the flow computer calculation expects to see a different meter performance.

The calibration performance parameters of the 4", sch 80, 0.63β cone meter are shown in page 14. The discharge coefficient is stated to be 0.803 ±1%. In straight pipe run (i.e. no disturbed flow) the uncertainty was 0.5%. However, when this parameter is applied as a diagnostic parameter, in order to reduce the chance of nuisance alarms, the assigned uncertainty is expanded to 1%. Let us consider the scenario of an incorrect discharge coefficient keypad entry of 0.83. This induces a +3.4% bias in the meter flow rate prediction. The choice of 0.83 is not entirely random. There are two reasons for choosing this value in this example. The first is the obvious and realistic scenario where the operator entering the value makes the error of missing the '0'. The second reason is that a prominent cone meter manufacturer's 'sizing program' estimates a 4", sch 80, 0.63β cone meters discharge coefficient to be 0.83. That is, before such a meter is manufactured and calibrated to find the true discharge coefficient (which in this case was found by CEESI to be 0.803) an initial estimate of 0.83 was offered. This example therefore shows the flow rate prediction bias induced if the operator was to accept this discharge coefficient estimate without calibrating the meter. In this case the bias is +3.4%. Other cases can have higher or lower biases. As described by Hodges et al [7], it is important to individually calibrate cone meters across their applications Reynolds numbers for optimum meter performance.

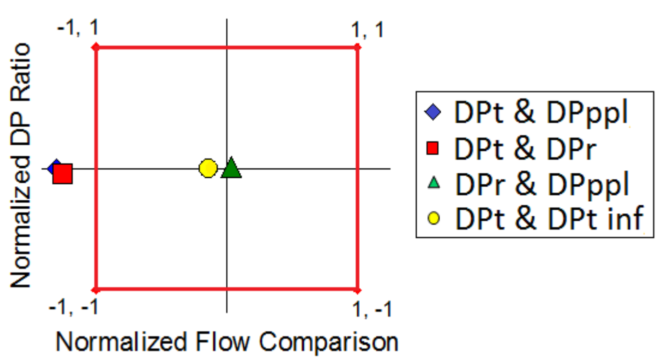

Figure 45. 4", 0.63β cone meter with erroneous Discharge Coefficient value.

Figure 45 shows the diagnostic result of this discharge coefficient keypad entry bias when using a randomly chosen 4", sch 80, 0.63β cone meter calibration point (at a Reynolds number of 1.44e6) from the straight run with undisturbed flow at the meter inlet. In this example the discharge coefficient was selected as the parameter incorrectly keypad entered into the software. It is just as likely that any of the six diagnostic parameters could be entered incorrectly. However, in all six cases the diagnostics show a meter system problem - that is, the diagnostic system can self-diagnose its own health.

5f. Miscellaneous Comments Regards the Diagnostic Examples

The cone meter malfunction examples chosen in this paper are only a small selection of what the diagnostic system is capable of seeing. Nevertheless, even with the small number of examples given, it is notable that the diagnostic pattern can vary depending on the malfunction.

DP Diagnostics has become aware that some engineers have mistakenly assumed that Prognosis is primarily nothing more than a comparison of the in-service to found PLR alone (i.e. y_1 only), with the diagnostic checks x_1, x_2, x_3, y_2 & y_3 being nothing more than redundant and superfluous repeats. **This is not true.** Each of the diagnostics are valuable in their own right. The six diagnostics x_1, x_2, x_3, y_1, y_2 & y_3 have different sensitivities for different DP meter geometries exposed to different metering problems. It is therefore incorrect to consider that y_1 is the prime diagnostic with the other diagnostics being superfluous. For example, section 5d shows that diagnostic check y_1 can sometimes be ineffective while other diagnostic checks are very effective. This is particularly true when the problem is with the 'expected' performance and the meter body is serviceable. All the diagnostics should be treated as equally relevant. Individually they are each valuable, but when used together the whole diagnostic system is greater than the sum of its parts. The combined diagnostics form an interwoven 'lattice' of diagnostics with significant strength compared to any individual diagnostic check used in isolation.

When all the diagnostic checks are used together, when a meter malfunctions, the resulting diagnostic pattern contains information as to what the source of the problem could and could not be. Such information is valuable to meter operators and maintenance crews. However, detailed discussion of cone meter diagnostic warning patterns is out-with the scope of this paper.

Six common cone meter malfunctions were chosen as diagnostic examples. These can be split into three groups:

- DP transmitters giving an erroneous DP reading (one example),
- malfunctions due to physical issues with or at the meter body, i.e. problems with the meters actual performance as 'found' (two examples),
- malfunctions due to the expected performance being erroneous, i.e. problems with the meters keypad entered 'expected' performance (three examples).

In ***all*** cases, including when the 'expected' / calibrated baseline data and geometry values were the source of the problem, the diagnostic system showed that the meters flow rate prediction was not trustworthy. That is, it is shown that the integrity of Prognosis is ***not*** reliant on the correctness of the calibration data and meter geometries keypad entered into the system. Prognosis is as capable of monitoring for calibration / baseline 'expected' performance errors as it is for physical meter malfunctions.

6. Conclusions

Baseline calibration and flow disturbance tests at CEESI on 4”, sch 80, 0.63β and 0.75β cone meters demonstrated that the cone meter is resistant to most real world flow disturbances, at least within this meter size and beta ratio range.

- The 0.63β cone meters flow rate prediction did not deviate by more than 1% across all flow disturbances tested.
- Only with the most extreme tests, that were conducted to guarantee that the very worst of real world flow disturbances had been exceeded, did the 0.75β cone meters flow rate prediction deviate by more than 1%.

Hence, it is concluded that cone meters with beta ratios of 0.75 are resistant to most flow disturbances.

Whilst the 0.75β cone meter was found to be resistant – it is not entirely resistant to flow disturbances. Some manufacturer’s early and overly optimistic claims of complete immunity has not helped a naturally cautious industry accept that the cone meter does indeed have an excellent, if not perfect, resistance to flow disturbances. There were three upstream pipe work induced flow disturbances that could cause a 0.75β cone meters flow rate prediction bias. These were:

- a single 90^0 bend
- a gate valve (50% open / closed)
- ***extreme*** swirl with expansion.

Only the 0.75β meter was tested with the single 90^0 bend. A slightly greater than 1% flow rate prediction bias was induced with the meter 0D downstream. Placing the meter at 5D downstream caused this bias to disappear.

Both the 0.63β & 0.75β cone meters were tested with the Half Moon Plate (HMP) mimicking a gate valve 50% closed. These results were not conclusive. The 0.75β meter was immune to the disturbance created by a HMP 5D upstream (i.e. a gate valve at approximately 3D) upstream of the meter. However, the 0.63β cone meter showed a slight flow rate prediction bias when a HMP was 6.7D (i.e. a gate valve at approximately 5D) upstream of the meter. By 8.7D (i.e. a gate valve at approximately 7D) upstream of the meter the bias had diminished to the border of the correctly operating meters uncertainty. Therefore, operators should allow for at least 7D upstream of a gate valve if they are to be assured of correct flow metering.

The 0.75β cone meter was unaffected by the 3” to 4” expansion 2D upstream of the meter. However, the same meter produced an extreme flow rate prediction bias when it was exposed to the very severe flow condition of extreme swirl and expansion 9D upstream of the meter. The 0.63β cone meter faired far better in this severe test, but it still had a small bias induced on the flow rate prediction. It is concluded that it is not advisable to attempt to measure flow with such extreme swirl.

The DP meter diagnostic tool ‘Prognosis’ was shown to be simple and effective. The diagnostic methods were shown to be of practical use even when the cone DP meter was experiencing significant flow disturbances. Disturbed flow that does not cause a flow rate prediction error does not cause false diagnostic alarms. Meter malfunctions do cause diagnostic system alarms. The simple addition of a downstream pressure tapping to the cone DP meter has produced a simple, practical and powerful tool to produce cone meter diagnostics.

References

1. Peters RJW., Steven R., "Tests on the V-Come Flow Meter at Southwest Research Institute® and the Utah State University in Accordance with the New API Chapter 5.7 Test Protocol", NSFMW 2004, St Andrews, UK.
2. "Testing Protocol for Differential Pressure Measurement Devices", API MPMS Chapter 22.2
3. Steven R., "Diagnostic Capabilities of DP Cone Meters" International Symposium of Fluid Flow Measurement, 2009, Anchorage, Alaska
4. Fish G. et al, "The Effects of Upstream Piping Configurations on Cone Meter and venture Meter Discharge Coefficients", NSFMW 2010, St Andrews, UK.
5. ISO 5167 – Part 4. "Measurement if Fluid Flow by Means of Pressure Differential Devices Inserted In Circular Cross Sectional Conduits Running Full – Part 4: Venturi Tubes".
6. Steven, R., "Diagnostic Methodologies for Generic Differential Pressure Flow Meters", NSFMW, St Andrews, Scotland, UK, October 2008.
7. Hodges C. et al "Cone DP Meter Calibration Issues", North Sea Flow Measurement Workshop Oct. 2009, Tonsberg, Norway.