Diagnostic Capabilities of ΔP Cone Meters

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1. Introduction

Differential Pressure (or "DP") flow meters have simple and relatively sturdy designs. This combination of simplicity and ruggedness make them both relatively inexpensive and reliable devices. Furthermore, their simplicity makes their operating principles easily understandable. For these reasons they are one of the most popular generic flow meter types. A DP Diagnostics ΔP cone meter sketch is shown in Figure 1, with a cut away of the meter wall to reveal the differential pressure producing cone element.

Cone DP meters are growing in popularity due to their proven immunity to the effects of most flow disturbances both upstream and downstream of the meter. That is, unlike most meter designs, the cone DP meter does not need extensive upstream and downstream straight pipe lengths, or flow conditioners, to meter the flow rate accurately. Therefore, the cone DP meter can be, and is, installed in many pipe work locations where no other flow meter could operate successfully (i.e. to a low uncertainty).

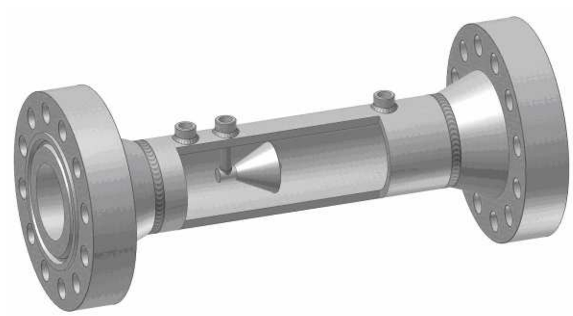

Fig 1. A Sketch of a DP Diagnostics ΔP Cone Meter

There is a growing interest in all flow meter self-diagnostic capabilities. Industry has seen increasing hydrocarbon product prices, more joint venture hydrocarbon production agreements and a continued drive to make power generation and factory processes more efficient. There has therefore also been a growing desire to reduce flow meter uncertainty and to guarantee flow meter performance. Only when a flow meter is known to be operating correctly is a meters uncertainty rating truly valid. Therefore, several of the various flow meter types on the market have self-diagnostic capabilities. However, due to the DP meters simplicity it was widely believed that there was no potential for DP meter self-diagnostics. In 2008, at the North Sea Flow Measurement Workshop, DP Diagnostics challenged that axiom (Steven [1]) by showing a patent pending technology that allowed any generic DP meter type to have a simple, inexpensive but effective diagnostic system.

The DP Diagnostics ΔP cone meter has a pressure tapping located downstream of the cone element on the meter body (see Figure 1). This extra pressure tapping is the key to DP meter self-diagnostics. In this paper, the DP Diagnostics ΔP cone meter self-diagnostics principles are discussed. Multiple data sets from cone DP meters in both correct and incorrect operational modes are shown to prove both the general diagnostics concept and to show the practical real world usefulness of such a system.

2. The DP Meter Classical and Self-Diagnostic Operating Principles

Figure 2 shows a sketch of a ΔP Cone Meter with the required instrumentation. A graph depicting the (simplified) pressure fluctuation through the meter body is also presented. Traditional cone DP meters read the inlet pressure (P_1) and one differential pressure (ΔP_t), that is, the difference in pressure between the inlet pressure tap (1) and the low pressure tap at the back of the cone (t). Note that the ΔP Cone Meter has a third

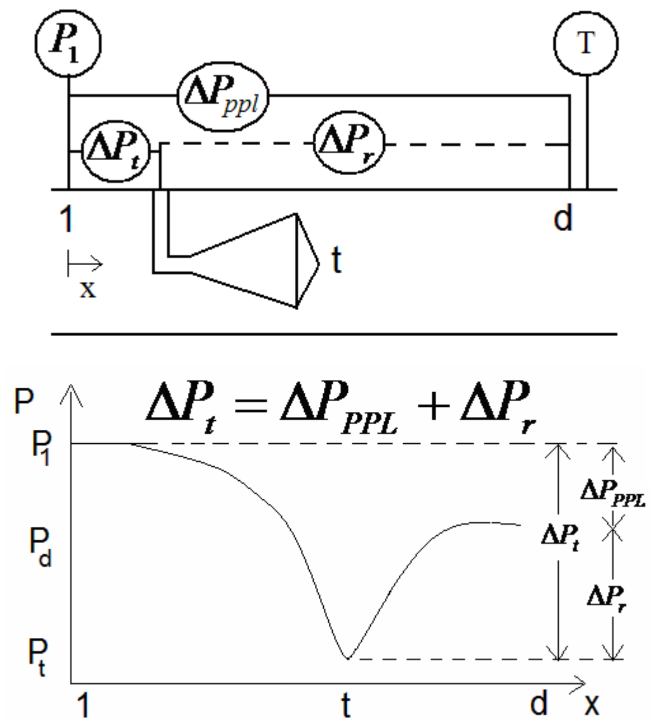

Fig 2. ΔP Cone Meter Sketch with Instrumentation and Pressure Fluctuation Graph.

pressure tap downstream of the cone. This simple addition to the traditional DP meter design allows the measurement of two extra DP's. That is, not only can the traditional DP be measured (ΔP_t), but it is now possible to measure both the "recovered" DP (ΔP_r) and the permanent pressure loss (ΔP_{PPL}, sometimes called the "PPL" or "total head loss").The recovered DP is the pressure difference between the downstream (d) and the low (t) pressure taps. The permanent pressure loss is the pressure difference between the inlet (1) and the downstream (d) pressure taps.

Note from Figure 2 that the sum of the recovered DP and the PPL must equal the traditional differential pressure. Hence, in order to utilize the three pressure taps to obtain the three DP's only two DP transmitters need be utilized. That is, only one extra DP transmitter needs to added to the traditional system, as the third DP can be calculated from the other two DP's by equation 1.

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

Traditional Flow Equation: $\dot{m}_t = EA_t Y C_d \sqrt{2\rho \Delta P_t}$, 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)

The traditional cone DP meter flow rate equation is the traditional generic DP meter flow equation, shown here as equation 2. That is, traditionally, all DP meter designs give one flow rate prediction found by this generic equation. However, with an additional downstream pressure tap three flow equations can be produced. That is, 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 equation predictions of the actual mass flow rate ($\dot{m}$) respectively. The symbol ρ represents the fluid density. Symbols E , A and A_t represent the velocity of approach (a constant for a set meter geometry), the inlet cross sectional area and the minimum (or "throat") cross sectional area through the meter respectively. Y is an expansion factor accounting for gas density fluctuation through the meter. (For liquids Y =1.) The terms C_d , K_r and K_{PPL} represent the discharge coefficient, the expansion coefficient and the PPL coefficient respectively. These are found by calibrating the DP meter and each can be set as constant values with set uncertainty ratings, or, may each 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 this case, as the Reynolds number (Re) is flow rate dependent, each of the three flow rate predictions must be independently obtained by an iterative method within the flow computer. A detailed derivation of these three flow rate equations is given by Steven [1].

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

Due to the existence of these three flow rate equations the DP Diagnostics ΔP Cone Meter is in effect three flow meters in one meter body. As there are three flow rate equations metering the same flow through the same meter body there is the potential to compare the three flow rate predictions and hence have a diagnostic system. Naturally, all three flow rate equations have individual uncertainty ratings (say x%, y% & z% as shown in equations 2 through 4). Therefore, it is unlikely that there would be a situation where, even if a ΔP Cone Meter was operating correctly, any two flow equations match each other precisely. In fact, there could always be some difference in flow rate predictions due to these uncertainty ratings. However, a correctly operating meter will have no difference between any two flow equations greater than the sum of the two uncertainties. (Equation 1 shows the DP's are inter-dependent parameters. From their subsequent relationships, and to reduce the likelihood of false diagnostic alarms, the sum of any two equation uncertainties is seen as more appropriate that the root mean square of the equation uncertainties.)

Traditional & PPL Meters % allowable difference (ϕ %): $\phi\% = x\% + z\%$ -- (6a)

Traditional & Expansion Meters % allowable difference (ξ %): $\xi\% = x\% + y\%$ -- (6b)

Expansion & PPL Meters % allowable difference (υ %): $\upsilon\% = y\% + z\%$ -- (6c)

This allows a self diagnosing system. If the percentage difference between any two flow rate equations is less than that equation pairs summed uncertainties (found from the meters calibration), then this indicates correct operation of the meter. In this case the traditional flow rate equations prediction can be trusted. If however, the percentage difference between any two flow rate equations is greater than that equation pairs summed uncertainties then this indicates a metering problem. In this case the traditional flow rate equations prediction should not be trusted. The three percentage differences are:

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)

This diagnostic methodology uses the three individual DP's to independently predict the flow rate and then compares these results. In effect, the individual DP's are therefore being directly compared. However, it is possible to take a different diagnostic approach. The Pressure Loss Ratio (or "PLR") is the ratio of the PPL to the traditional DP. The PLR is constant for DP meters operating with single phase homogenous flow. This is indicated by ISO 5167 [2]. Therefore, the ΔP Cone Meter has a constant PLR for a set geometry. Rewriting Equation 1 gives:

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

As we know the PLR is a set value for a given geometry DP meter then equation 1a is also showing that the ratio of the recovered DP to traditional DP must then also be constant. In turn this means that the ratio of the recovered DP to PPL must then also be constant. That is, all DP ratios available from reading the three DP's are constant values for any given DP meter and can be found by the same calibration that finds the three flow coefficients. Thus we have:

PPL to Traditional DP ratio (PLR): $\left(\Delta P_{PPL} / \Delta P_t\right)_{cal}$, uncertainty ± a%

Recovered to Traditional DP ratio (PRR): $\left(\Delta P_r / \Delta P_t\right)_{cal}$, uncertainty ± b%

Recovered to PPL DP ratio (RPR): $\left(\Delta P_r / \Delta P_{PPL}\right)_{cal}$, uncertainty ± c%

The calibration of the meter gives both the value and the uncertainty of the DP ratio values (i.e. the scatter in the data). Here then is another method of diagnosing the health of the DP meter. The actual DP ratios found in service can be compared to the calibrated values. Let us denote the difference between the actual pressure loss ratio (i.e. the PPL to traditional DP) and the calibrated value as α. Let us denote the difference between the actual recovered DP to traditional DP ratio and the calibrated value as γ. Let us denote the actual difference between the recovered DP to PPL and the calibrated value as η. These values are found by equations 8a to 8c.

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

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

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

The standard calibration of the ΔP Cone Meter produces six meter parameters with nine associated uncertainties. These six parameters are the discharge coefficient, expansion flow coefficient, PPL coefficient, PLR, recovered to traditional DP ratio (or "PRR" for **P**ressure **R**ecovery **R**atio) and the recovered to PPL DP ratio (or "RPR" for **R**ecovered to **P**PL **R**atio). The nine uncertainties are the six parameter uncertainties and the three flow rate inter-compariosn uncertainties. ***This calibration information defines the meters correct operating mode***. Any deviation from this mode beyond the acceptable uncertainty limits is a warning to the meter operator that something is not correct and the traditional meter output is therefore no trustworthy. Table 1 shows the six possible situations that should signal an alarm.

No Alarm	ALARM	No Alarm	ALARM
$\phi\ \% > \psi\%$	$\phi\ \% < \psi\%$	$a\ \% > \alpha\%$	$a\ \% < \alpha\%$
$\xi\ \% > \lambda\%$	$\xi\ \% < \lambda\%$	$b\ \% > \gamma\%$	$b\ \% < \gamma\%$
$\upsilon\ \% > \chi\%$	$\upsilon\ \% < \chi\%$	$c\ \% > \eta\%$	$c\ \% < \eta\%$

Table 1. The DP Meter possible diagnostic results.

For practical real time use, this diagnostic information must be easily accessible and understandable at a glance by any meter operator. As the diagnostic is qualitative rather then quantitative a graphical representation of the meters health could be simple but effective. It is therefore beneficial to plot the results on a graph. A simple option is to treat each of the three DP pair comparisons separately. That is, for any given pair of DP's, make one axis indicate the percentage difference in the two flow rate predictions and the other axis indicate the percentage difference of the actual to calibrated DP ratio value. The calibration has set the maximum allowable percentage value of each. Therefore a box can be drawn on a graph, centred at the origin, where the box has corner co-ordinates set by calibration inputs. For example, let us discuss the DP pair comprising of the tradition DP and the PPL. The co-ordinates of the corner of the calibrated diagnostic box and a typical actual diagnostic result from the meter would be as shown in Figure 3.

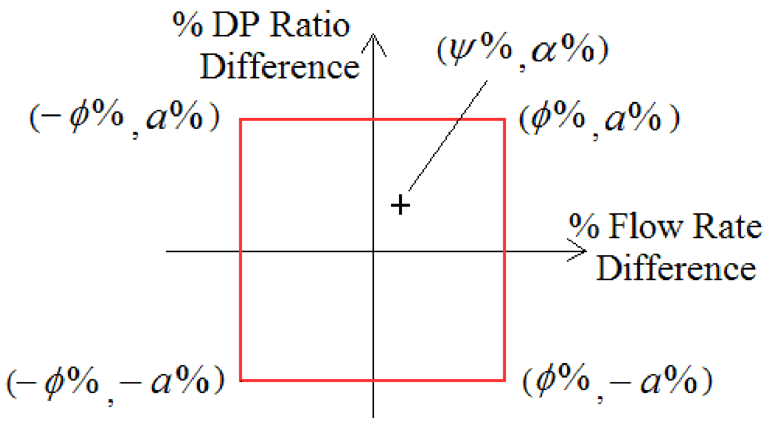

Fig 3. A DP Meters, DP pair diagnostic calibration box and actual diagnostic result.

Therefore, if in service, the flow computer places the actual diagnostic point of the tradition DP and the PPL comparison , i.e. point ($\psi\%, \alpha\%$), somewhere in or on the calibrated diagnostic box the meter is shown to be within normal operational limits and hence probably in good health. However, if the actual diagnostic point fell outside the calibrated diagnostic box the meter is shown to be not operating within normal operational limits. An alarm indicates a potential metering problem and the fact that the traditional flow rate prediction may not be trustworthy.

Naturally, if such a diagnostic plot is used, the diagnostic system requires three calibrated diagnostic boxes (all found from a single calibration) for the three DP pairs. Three separate diagnostic boxes would reduce the effectiveness of the diagnostic visual aid as for a given screen size, the boxes would be relatively small and more than a glance would be required to monitor meter health. It is therefore beneficial to superimpose all three calibrated diagnostic boxes on to one graph. However, this would clutter the single graph thereby potentially making it confusing. There could be three different sized calibrated diagnostic boxes over lapping each other, with individual diagnostic points inside one box and outside another. A solution to this problem is to normalize the data. This can reduce the triple graph visual diagnostic display to one single graph with a single normalized calibrated diagnostic box and three normalized data points which can be easily seen to be in, on or out of the box. The normalization procedure loses none of the diagnostic information. It is now discussed.

Calibrating a DP meter with a downstream pressure tap produces six parameters and their associated uncertainties. However, it also sets the maximum allowable difference between the three mass flow rate comparisons (i.e. $\phi\%, \xi\%$ & $\upsilon\%$) to go along with fore mentioned DP ratio uncertainties (i.e. $a\%, b\%$ & $c\%$). The non-normalized traditional DP and PPL comparison calibrated diagnostic box is created by having corner co-ordinates ($\phi\%, a\%$), ($\phi\%, -a\%$), ($-\phi\%, -a\%$) & ($-\phi\%, a\%$). The non-normalized traditional DP and recovered DP comparison calibrated diagnostic box is created by having corner co-ordinates ($\xi\%, b\%$), ($\xi\%, -b\%$), ($-\xi\%, -b\%$) & ($-\xi\%, b\%$). The non-normalized PPL and recovered DP comparison calibrated diagnostic box is created by having corner co-ordinates

($\upsilon\%, c\%$), ($\upsilon\%, -c\%$), ($-\upsilon\%, -c\%$) & ($-\upsilon\%, c\%$). The three points plotted on these three graphs are ($\psi\%, \alpha\%$) for the traditional DP and PPL comparison, ($\lambda\%, \gamma\%$) for the traditional DP and recovered DP comparison, and ($\chi\%, \eta\%$) for recovered DP and PPL comparison respectively. However, we can normalize ***all*** the data. For each box corner co-ordinate, divide the abscissa co-ordinates by the modulus of the maximum allowable mass flow rate difference and divide the ordinate co-ordinates by the modulus of the maximum allowable DP ratio difference. For example, when considering the traditional DP to PPL pair, divide all the abscissa co-ordinates by $\phi\%$ and divide all the ordinate co-ordinates by $a\%$.

By definition, this sets all three normalized calibrated diagnostic boxes to corner normalized co-ordinates: ($1, 1$), ($1, -1$), ($-1, -1$) & ($-1, 1$). Therefore all three different sized non-normalized calibrated diagnostic boxes are converted to the same size normalized calibrated diagnostic box. That is one normalized calibrated diagnostic box can therefore represent all three non–normalized boxes. On this single normalized graph with the normalized diagnostic box, we can plot the three normalized diagnostic points from the three DP pairs. These points were normalized by the abscissa and ordinate values being divided by the maximum allowable mass flow rate and DP ratio differences respectively. That is, these diagnostic points are ($\psi/\phi, \alpha/a$), ($\lambda/\xi, \gamma/b$) & ($\chi/\upsilon, \eta/c$). The normalized graph is shown as Figure 4. Note that in this random theoretical example all three points are within the diagnostic box indicating that such a DP meter would be operating within the limits of normality, i.e. no metering problem is noted.

It is possible to reduce the diagnostic box further, to the first quadrant of the graph, if we only dealt with the modulus (i.e. absolute) values of the diagnostic parameters. However, this is not practically advantageous, as the diagnostic still depends on the points falling within or out with the limits of the diagnostic box. Such a reduced diagnostic box is not regarded as much clearer than the Figure 4 design. Furthermore, reducing the diagnostic box to the first quadrant loses information as the direction of DP drift during a metering problem is removed. Hence, the Figure 4 design is preferable.

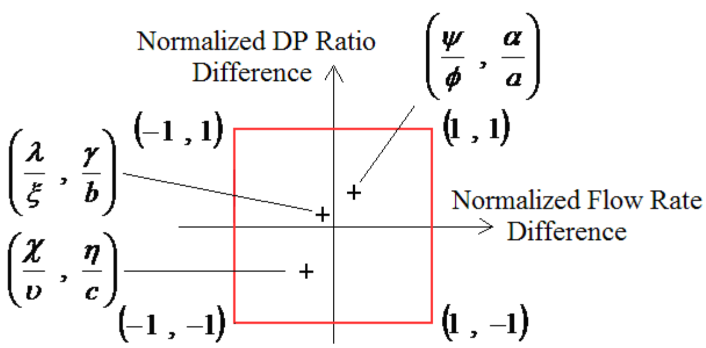

Fig 4. A normalized diagnostic calibration box with normalized diagnostic result.

Finally, it may be asked whether it is necessary to use both diagnostic techniques, i.e. the flow rate comparisons and the DP ratio comparison with the calibrated values. Both use the same fundamental inputs, i.e. the three DP's. It could therefore be assumed that if the DP relationships are as they should be then both diagnostic techniques will indicate correct meter operation but if the DP's relationships are not as they should be then both diagnostic techniques will indicate incorrect meter operation. However, from experience, it has been found that the two techniques can have slightly different sensitivities to particular problems. Generally, it is true that if one technique sets off an alarm the other does likewise. However, initial testing of the methodology suggests that the DP ratio technique is usually slightly more sensitive to metering abnormalities than the meter comparison technique. That is, the DP ratio technique can typically see smaller problems than the flow rate comparison technique. Therefore, if both techniques state there is no problem then there is no alarm and the meter is shown to be operating correctly. The traditional flow rate prediction can be trusted. If both techniques state there is a problem a "general alarm" is tripped and the operator knows that a potential metering problem has occurred and he traditional flow rate prediction can not to be trusted. If one technique trips the alarm and the other technique does not then the operator is warned by an "amber alarm". This indicates the possibility of a *small* problem, but at worst any traditional flow rate prediction bias is small. Hence, it is greatly beneficial to use both techniques simultaneously, especially as the computational power required is relatively small. There are therefore three alarm settings, no alarm, amber alarm, general alarm. Figure 4a shows the zones of no alarm, amber alarm and general alarm. In the following sections a ΔP Cone Meter is calibrated, the normalized diagnostic box is created and then normal and abnormal operation data is shown in relation to this normalized diagnostic box.

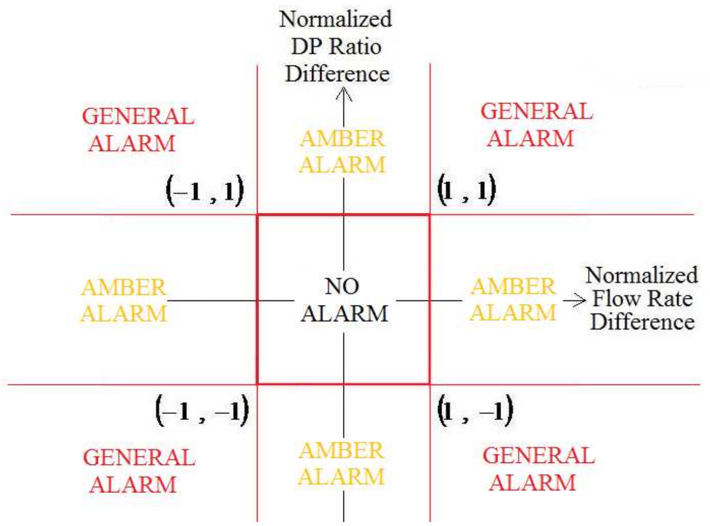

Fig 4a. Normalized diagnostic calibration box with alarm zones.

3. ΔP Cone Meter Performance

The ΔP Cone Meter is a successful meter in part due to the designs known resistance to upstream and downstream disturbances. However, like all DP meters the ΔP Cone Meter could greatly benefit from having diagnostic capabilities. In order for the ΔP Cone Meter to have a ***practical*** diagnostic capability the methodology must be proven to work in all typical meter applications. That is, the diagnostic parameters are typically set from meter calibrations where there are long straight upstream and downstream pipe lengths. However, these results must hold true for all typical real world installations. In other words, it must be shown that the just like the discharge coefficient, all the other calibration parameters, i.e. the expansion coefficient, PPL coefficient, the PLR, the PRR and the RPR, are suitably resistant to common flow disturbances. For the DP meter diagnostic method to work for a ΔP Cone Meter, ***all*** the diagnostic parameters must have resistance (to an acceptable level) to disturbed flow profiles. Otherwise, disturbed flow could set of a false alarm. DP Diagnostics therefore built a 4", schedule 80, 0.63 beta ratio ΔP Cone Meter (with a downstream pressure tap) and calibrated the meter at CEESI with long straight pipe runs. In order to appreciate the relative position of the cone to the components causing disturbances, note that the centre line of the cone support is 2D from the inlet flange face and 5.25D from the outlet flange face (as the meter is 7.25D long). All diagnostic parameters were recorded from the direct measurement of all three DP's. This baseline set up is shown in Figure 5. All the resulting calibration parameters then had to be repeatedly checked against a variety of typical real world installations.

The American Petroleum Institutes DP meter testing protocol (API 22.2) gives some typical adverse pipe work DP meter installation examples. However, in this series of tests DP Diagnostics not only matched the API suggested test installations but sometimes went further and tested this ΔP Cone Meter under even more extreme installations. Tests included, a 90^0 double out of plane bend (DOPB) at 5D, 2D and 0D upstream of the meter. The 0D installation is shown as Figure 6. Then a half moon orifice plate (HMOP) was placed at 2D downstream of this configuration. In these tests the plate always blocked the top half of the pipe area. Note that this models a gate valve at 50% closed. A real gate valve has the gate centred on the valve seat with flanges at either side to connect it to the pipe system. Hence, typically the gate itself is 1.5 to 2 D from the adjacent flange it is being connected to. Therefore, when installing a HMOP between 2 flanges, allow 2D from the plate to model a gate valve installation at 0D. Hence Figure 7 shows a test simulating a DOPB at 0D upstream and gate valve 50% closed at 0D downstream. Figure 8 shows a test simulating extreme

Fig 5. Baseline

Fig 6. DOPB, 0D up

Fig 7. DOPB 0D up & HMOP 2D down

Fig 8. DOPB 0D up & TOPB down

Fig 9. HMOP 6.7D up

Fig 10. HMOP 8.7D up

pipe work issues. The inlet is a DOPB at 0D and the outlet is a triple out of plane bend (TOPB) at 0D. Figure 9 & 10 show the HMOP installed at 6.7D and 8.7 D upstream of the ΔP Cone Meter. This set up models a gate valve at approximately 5D and 7D upstream of the ΔP Cone Meter. Figure 11 shows the HMOP at 2D downstream of the meter. This models a gate valve 50% closed at 0D downstream of the ΔP Cone Meter. Finally, Figure 12 shows a very extreme installation of a 3" swirl generator (i.e. a jammed 3" turbine meter) creating 54^0 before expanding to 4" at 9D upstream of the ΔP Cone Meter.

The base line calibrated results for the six calibration parameters are shown in Figures 13 & 14 along with the data fit uncertainties. The baseline tests were carried out at two nominal pressures, i.e. 17 and 41 Bara. Figure 13 shows the flow coefficients. A constant discharge coefficient fitted all the data to an uncertainty

Fig 11. HMOP 2D down

Fig 12. 3" Swirl Generator + Expansion 9D up

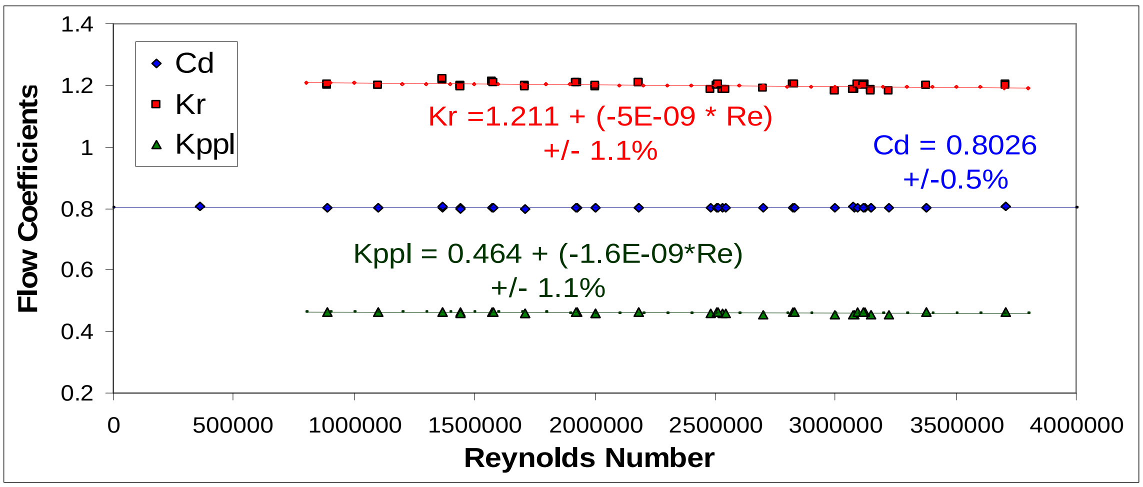

Fig 13. 4", 0.63 beta ratio, ΔP cone meter baseline flow coefficient results.

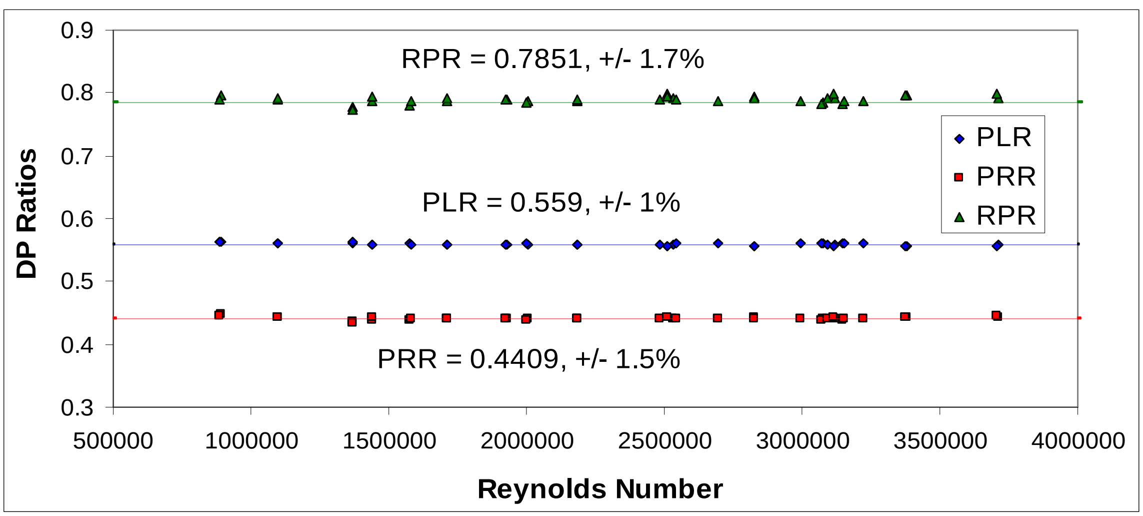

Fig 14. 4", 0.63 beta ratio, ΔP cone meter baseline DP ratio results.

of ±½%. As the traditional flow rate equation (i.e. equation 2) accounts for fluid expansibility the change of gas density through the meter is fully accounted for and independent of the discharge coefficient. The expansion and the PPL flow coefficients have linear data fits to the Reynolds number, both with a ±1.1%

uncertainty. Note that the expansion and PPL flow rate equations (i.e. equation 3 & 4) do not have expansibility factors and hence with gas flows the effect of density changes through the DP meter appears as scatter in the expansion and the PPL flow coefficients. This is partially the reason why these coefficients have higher uncertainty than the discharge coefficient. If dedicated expansibility factors for the expansion and PPL flow rate equations were to be created these uncertainty levels would reduce. Nevertheless, note that even so, with the expansibility effect producing scatter in the expansion and the PPL flow coefficients, the linear fits across both pressures data sets still gave a relatively low uncertainty of ±1.1%.

Figure 14 shows that the DP ratios are constant for set DP meter geometries and independent of the single phase flow conditions, i.e. fluid density and flow rate. For constant averaged values the scatter in the data was relatively small. Hence, the DP ratios can be compared to calibrated values to create a diagnostic capability. However, as it is known in reality this type of meter will be used in difficult installations the validity of these six parameter uncertainty readings has to be investigated for when there is extreme flow disturbances upstream and downstream of the meter. Figure 15, 16 & 17 show the calibrated discharge, expansion & PPL coefficients across all the extreme disturbances tested respectively. Figure 18, 19 & 20 show the PLR, PRR & RPR across all the extreme disturbances tested respectively. Due to the extensive testing, and the fact that it was known pressure does not affect the parameters, all flow disturbance tests were restricted to being carried out at one nominal pressure of 17 Bara.

Figure 15 shows that as expected, the ΔP cone meter is extremely resistant to disturbed flow. Only two installations causes the predicted discharge coefficient to vary beyond the baseline ±½% uncertainty. That is the traditional cone DP meter is immune to the DOPB at 5D, 2D and even 0D upstream. It is immune to the DOPB at 0D upstream with the HMOP at 2D downstream. It is immune to the DOPB at 0D upstream and TOPB at 0D downstream as well as a straight run into the meter with a HMOP at 2D downstream. The only installations that caused any significant effect on the discharge coefficient were the HMOP upstream installation and the swirl generator with expander upstream installation. Both installations are extreme, and therefore relatively rare installations in industry. The HMOP at 6.7D models a gate valve 50% closed at approximately 5D upstream. This is the very short upstream distance for such an extreme disturbance. The effect is seen to be an average rise in discharge coefficient above the calibrated value of about +0.8%. Extending the HMOP upstream distance to 8.7D (i.e. a gate valve at 7D) improves the situation by dropping the disturbance induced bias to an average +0.4% above the calibrated value and within the baseline +0.5% uncertainty band. The extreme swirl with expansion 9D upstream caused a drop in the actual discharge coefficient below the baseline calibrated uncertainty limits at the lower Reynolds numbers. Even so all the discharge coefficient data from all the disturbance tests are spread around the baseline calibrated value to ±1%. Nevertheless, DP Diagnostics suggests valves are installed no closer then 7D upstream of the cone DP meter and inlet swirl conditions are limited to *moderate* swirl (i.e. considerably less than 54^0) especially if there is an expansion close by upstream.

Figures 16 & 17 show the disturbance effects on the expansion and PPL flow coefficients. These parameters resistance to disturbed flow is critical to the applicability of the diagnostic methodology. Clearly both parameters are more affected than the discharge coefficient, but, crucially they are also both still relatively immune to the disturbances in the flow. The different disturbances cause the spread of data around the expansion coefficient baseline data fit to increase from ±1.1% to ±2.5%. There is no one particular disturbance which stands out as causing a particularly large expansion coefficient deviation. The different disturbances cause the spread of data around the PPL coefficient baseline data fit to also increase from ±1.1% to ±2.5%. However, the PPL coefficient is clearly more resistant to most disturbances than the expansion coefficient. In fact only the extreme swirl with expansion 9D upstream caused the over all uncertainty rating to rise above ±1.5%. Nevertheless, all the PPL coefficient data, regardless of the type of disturbance tested falls within an uncertainty rating of ±2.5%.

Figures 18, 19 & 20 show the effect the disturbances had on the DP ratios. The magnitude of the uncertainty increase due to the disturbances was significantly larger for the DP ratios than the flow coefficients. The PLR uncertainty was increased from ±1% to ±4.5%. The PRR uncertainty was increased from ±1.5% to ±6%. The RPR uncertainty was increased from ±1.7% to ±10%. It is clear from the Figures that again, it is the swirl generator with the expander 9D upstream that accounts for most of this increase. It may initially look like this large DP ratio uncertainty increase caused by real world installation effects

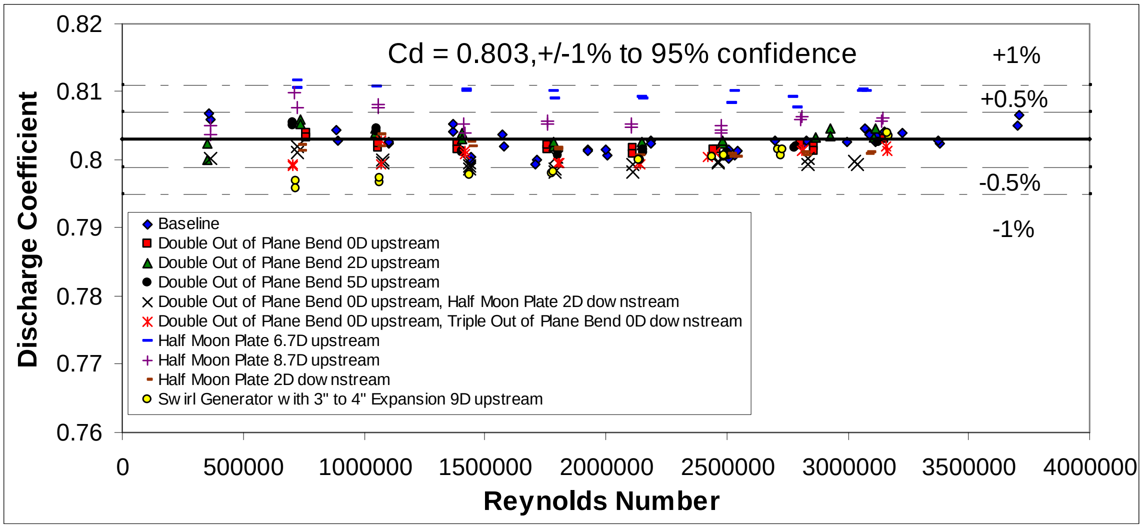

Fig 15. 4”, 0.63 beta ratio, ΔP cone meter disturbed flow discharge coefficient results.

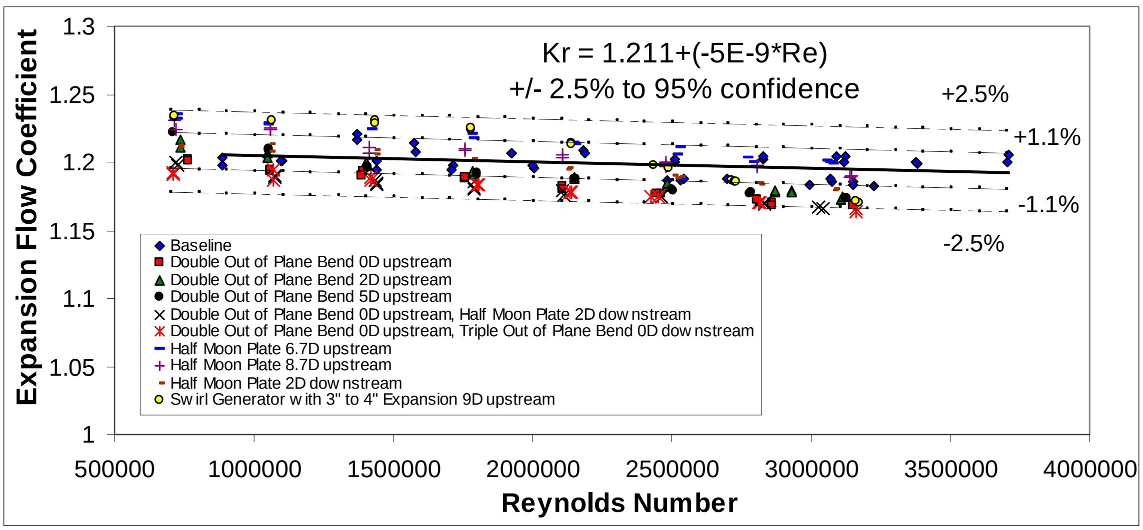

Fig 16. 4”, 0.63 beta ratio, ΔP cone meter disturbed flow expansion coefficient results.

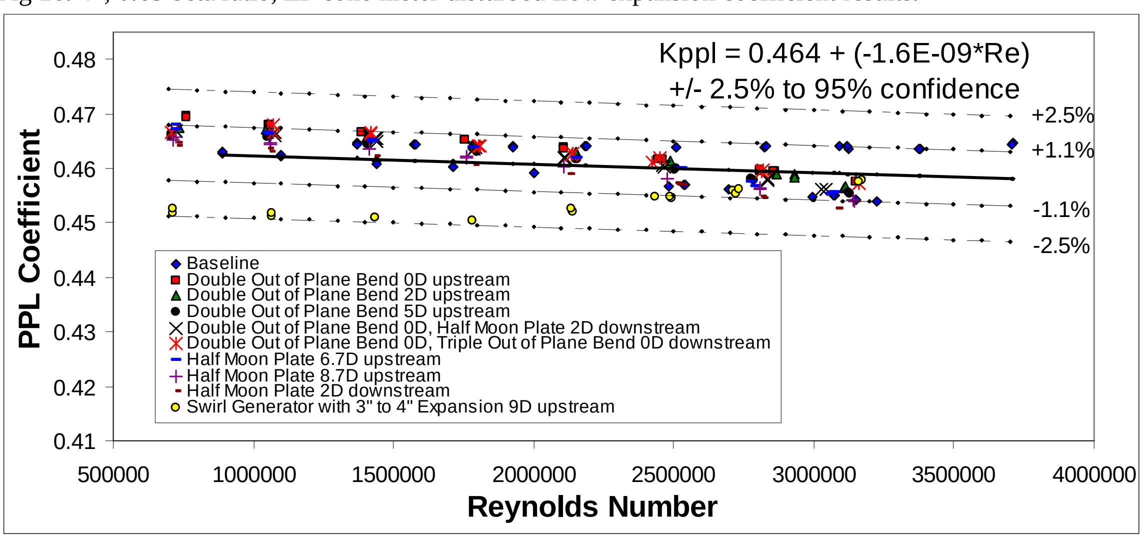

Fig 17. 4”, 0.63 beta ratio, ΔP cone meter disturbed flow PPL coefficient results.

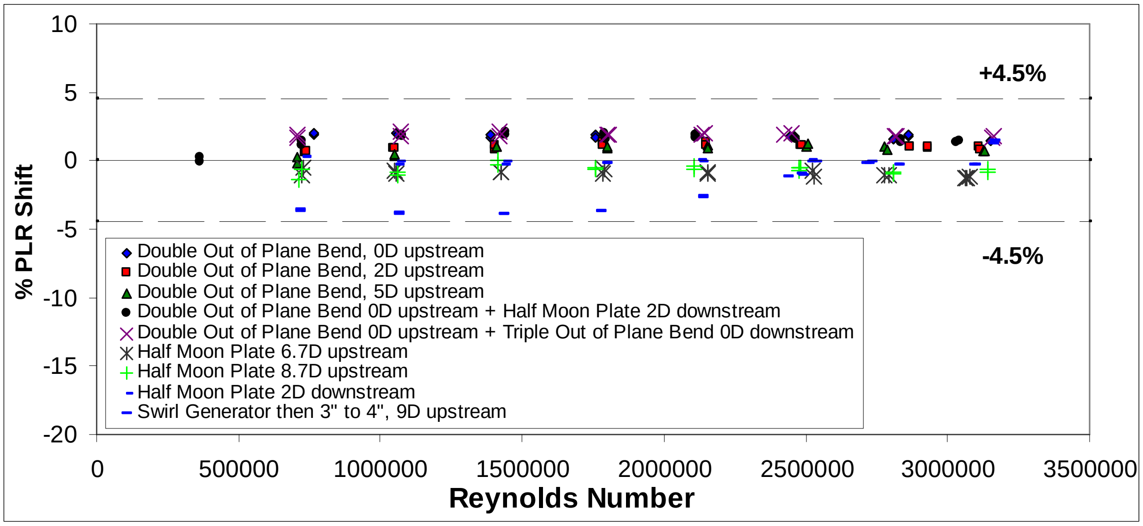

Fig 18. 4”, 0.63 beta ratio, ΔP cone meter disturbed flow PLR results.

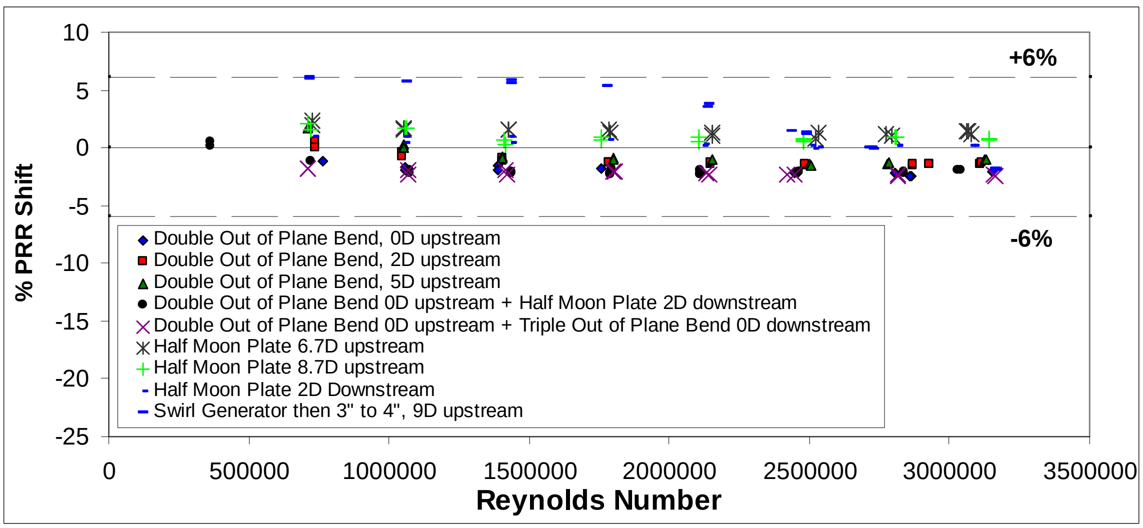

Fig 19. 4”, 0.63 beta ratio, ΔP cone meter disturbed flow PRR results.

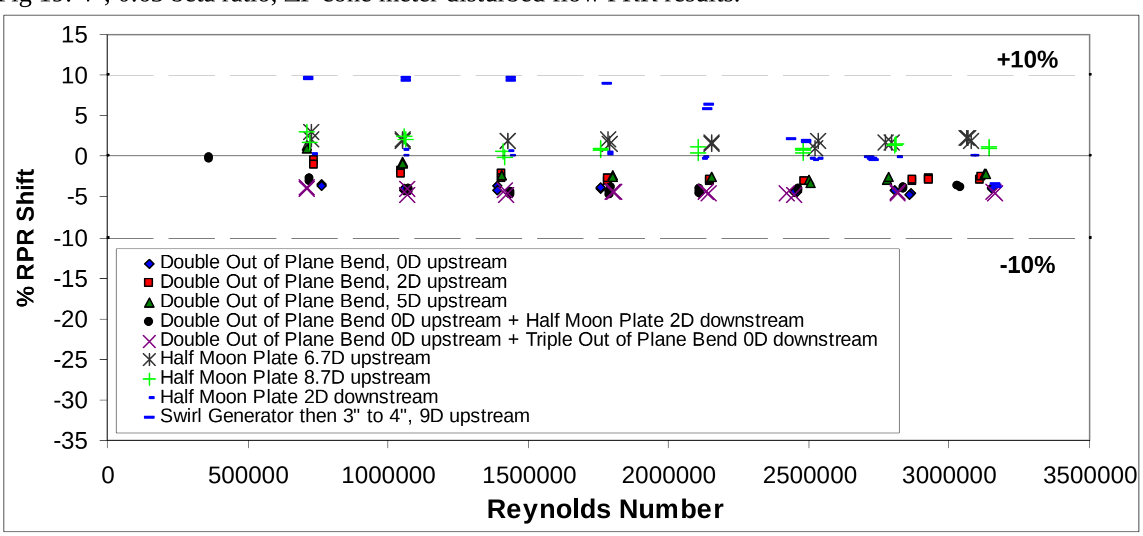

Fig 20. 4”, 0.63 beta ratio, ΔP cone meter disturbed flow RPR results.

could adversely affect the diagnostic methodologies practicality. However, it will now be shown that the DP ratios can be so greatly affected by common cone DP meter problems that these uncertainty limits are still of great practical use.

The DP Diagnostics ΔP cone meter has now been calibrated with a baseline to find the discharge coefficient, expansion coefficient, PPL coefficient, the PLR, the PRR and the RPR. The baseline is the standard DP meter calibration configuration. However, we must include the uncertainty that may be added by the potential real world disturbances. Note that the discharge coefficient (i.e. the factor that is used to produce the primary flow rate prediction) has a baseline uncertainty of ±0.5%. Only the gate valve at 5D or the swirl generator with expander 9D upstream caused the discharge coefficient to deviate beyond this baseline uncertainty. As the author advises a minimum of 7D upstream for gate valve installations we can ignore this 5D upstream result. Furthermore, the swirl generator with expander 9D upstream only had low Reynolds number data points where the discharge coefficient deviated beyond the baseline uncertainty. Therefore maintaining a stated discharge coefficient uncertainty of ±0.5% is reasonable. However, for the purpose of diagnostics only, a more liberal uncertainty rating helps avoid the possibility of false alarms being tripped by the system. Therefore, the diagnostic system has the maximum uncertainties found for all six parameters in the baseline and flow disturbance tests. Therefore we have:

$C_d = 0.803$, ±1% (i.e. ±x%) PLR = 0.559, ±4.5% (i.e. ±a%)

$K_r = 1.211 + (-5E - 9 * \mathrm{Re})$, ±2.5% (i.e. ±y%) PRR = 0.4409, ±6.0% (i.e. ±b%)

$K_{PPL} = 0.464 + (-1.6E - 9 * \mathrm{Re})$, ±2.5% (i.e. ±z%) RPR = 0.7851, ±10.0% (i.e. ±c%)

It is reasonable to assume that as the disturbances are about as extreme as can be practically found in service no cone DP meters will have any higher uncertainty in any of the parameters than those uncertainties being used here. In addition to the six parameters and their associated uncertainties the calibration also gives another set of results, i.e.:

Traditional & PPL Meters max % rms $\phi\% = (\pm 1\%) + (\pm 2.5\%) = \pm 3.5\%$

Traditional & Expansion Meters max % rms $\xi\% = (\pm 1\%) + (\pm 2.5\%) = \pm 3.5\%$

Expansion & PPL Meters max % rms, $\upsilon\% = (\pm 2.5\%) + (\pm 2.5\%) = \pm 5.0\%$

Hence, we have the calibrated information to plot each flow result on the normalized diagnostic box for this particular meter, i.e. plot ($\psi/\phi, \alpha/a$), ($\lambda/\xi, \gamma/b$) & ($\mu/\upsilon, \eta/c$) as shown in Figure 4a. Figure 21 shows this plot (although the HMOP 6.7D upstream data has been disregarded as DP Diagnostics does not condone meter installation at this location). Note that each flow point tested for each installation produces three points on the normalized diagnostic box. Clearly, from Figure 21 the swirl generator with expansion at 9D upstream of the meter caused by far the greatest deviation from the origin. However, by design this installations affects are not enough to set off any alarm. Nevertheless, it is still advisable while allowing for this installation in the diagnostic settings to avoid actually installing the meter in such an extreme application.

Note that, as these installation effect tests were so extreme they should match or exceed most real world application effects. In reality, each DP Diagnostics ΔP Cone Meter is typically calibrated with straight length pipe runs. Therefore, the uncertainties of the actual six parameters found in this idealized installation calibration are significantly smaller than the uncertainties actually applied by DP Diagnostics to account for real world installation effects. This allows the diagnostic method to account for all real world installation affects not seen under standard calibration. This therefore avoids false alarms being triggered due to distorted flow affects which do not significantly affect the traditional meters flow rate prediction.

It has now been shown that a normalized diagnostic box can easily be set up as part of the DP meters calibration procedure. This takes little more effort than for a standard DP meter calibration. It is now appropriate to investigate what happens when the meter is subsequently taken to the application and, unbeknown to the operator, used under abnormal flow rate error producing, conditions.

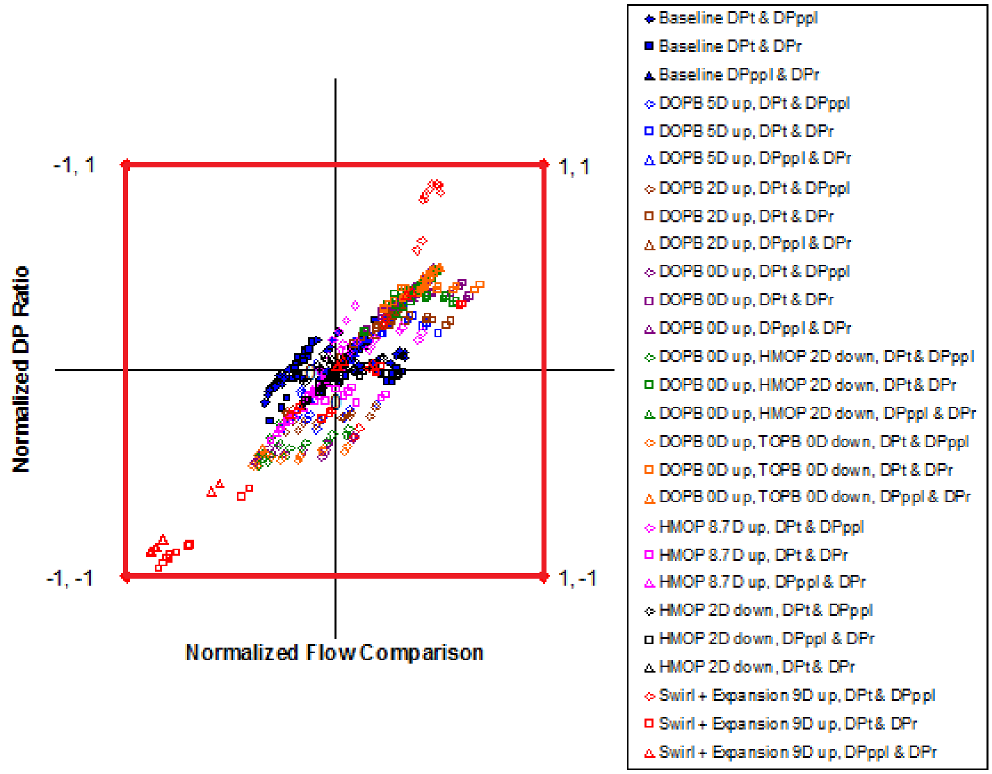

Fig 21. A normalized diagnostic box created by calibration with all calibration data.

4. <u>ΔP Cone Meter Performance in Abnormal Operating Conditions</u>

There are three common problems when operating a DP meter. These are a partial blockage of the meter, incorrect DP readings due to DP transmitter issues and damage to the DP meter wetted components. Therefore, let us look at each of these in turn.

4a. <u>ΔP Cone Meter Performance with a Partially Blocked Minimum Flow Area</u>

DP meters obstruct flow. The primary element (i.e. the cone assembly for ΔP Cone Meter) blocks part of the pipe cross sectional area to produce the required DP. This obstruction can therefore act as a net to debris flowing in the pipe. Debris trapped at the cone can, and often does, cause significant flow metering errors. Traditionally, there is no accepted method for a DP metering system to self diagnose such a problem.

In 2008, Steven [1] simulated a field blockage by trapping a large coupling plug at the cone of a 4”, 0.75 beta ratio meter. A very significant flow rate error was produced by the traditional flow rate equation. However, it was shown that inter-comparisons of the three flow rate equations indicated a major flow rate prediction error. In 2009 DP Diagnostics went further and tested a very much smaller blockage on the 4”, 0.63 beta ratio ΔP Cone Meter discussed above. That is, a small nut (producing a relatively small error compared to the previous large plug blockage test) was trapped at the cones edge. (This is about as small an object as can get trapped by this cone size.) The blockage is shown in Figure 22 & 22a. Furthermore, for realism, this blockage was applied when the meter was installed in a couple of the worst of the aforementioned non-ideal installations, i.e. a DOBP 0D upstream and a HMOP installed 2D downstream (see Figure 7), and then, with the swirl generator and expander at 9D upstream (see Figure 12).

Figure 23 shows the three flow rate prediction results. Clearly, the traditional meter gave very significant errors for the nut trapped in both installations. Interestingly though, they were not the same. The DOPB at 0D upstream with the HMOP at 2D downstream had a traditional flow rate error in the order of +5%, whereas the swirl generator with expander at 9D gave a different error in the order of +8%. Furthermore,

Fig 22. Trapped nut looking downstream

Fig 22a. Trapped nut looking upstream

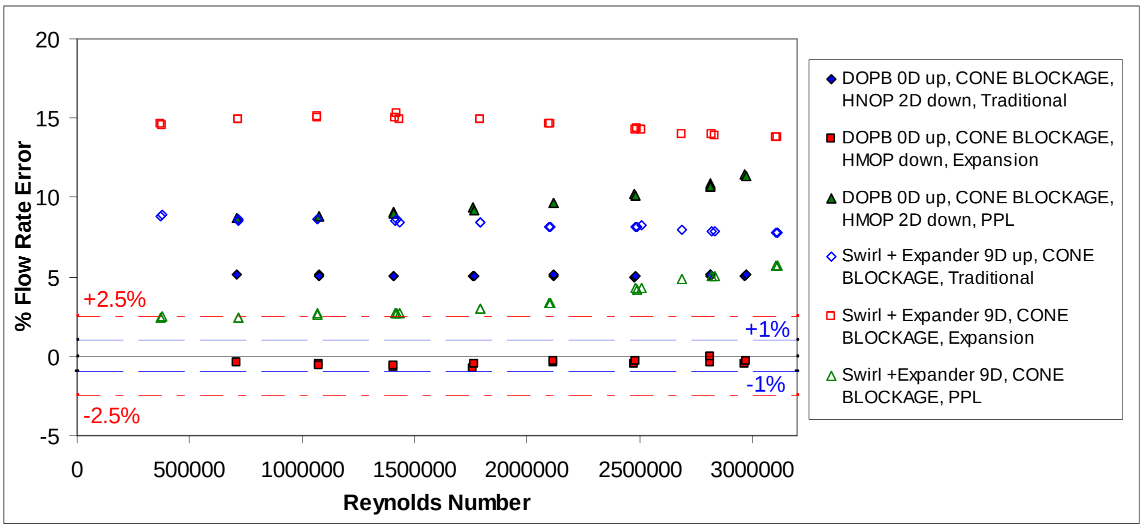

Fig 23. 4", 0.63 beta cone meter flow rate results with trapped nut in two installations.

the other two prediction methods gave significantly greater differences. The DOPB at 0D upstream with the HMOP at 2D downstream had an expansion flow rate error that showed no significant error, whereas the swirl generator with expander at 9D gave an error in the order of +15%. Also, The DOPB at 0D upstream with the HMOP at 2D downstream had a PPL flow rate error in the order of +10%, whereas the swirl generator with expander at 9D gave an error in the order of +4%.

The DP ratio comparisons with the calibrated values are shown in Figure 24. The precise reason for these significantly different results for the same meter with the same obstruction in two different installations is not known. However, it is clearly some consequence of the meters disturbed inlet flows relations with the blockage and pressure tapping position. Although, the precise reasons for these differences are not well understood, it should be noted that the sole aim of the diagnostic system is to flag any potential metering problems. Therefore, this issue is of academic interest only and further discussion is out with the scope of this paper. However, it has been shown that we can identify incorrect meter operation by using the diagnostic method. Hence, Figure 25 shows the results of applying the DP Diagnostics diagnostic methodology to both installations where the trapped nut was tested.

Figure 25 shows the normalized diagnostic box and data where the meter is operating incorrectly. Each data point recorded (i.e. each set of traditional, recovered and PPL DP's) produce three points on the graph. For both cases, all the data across both the full turndowns are clearly outside the normalized diagnostic box. Note that although all data is well outside the box some data falls into the amber alarm zone. This is due to the DP ratio comparison showing a problem and the meter comparison not showing a problem. This shows

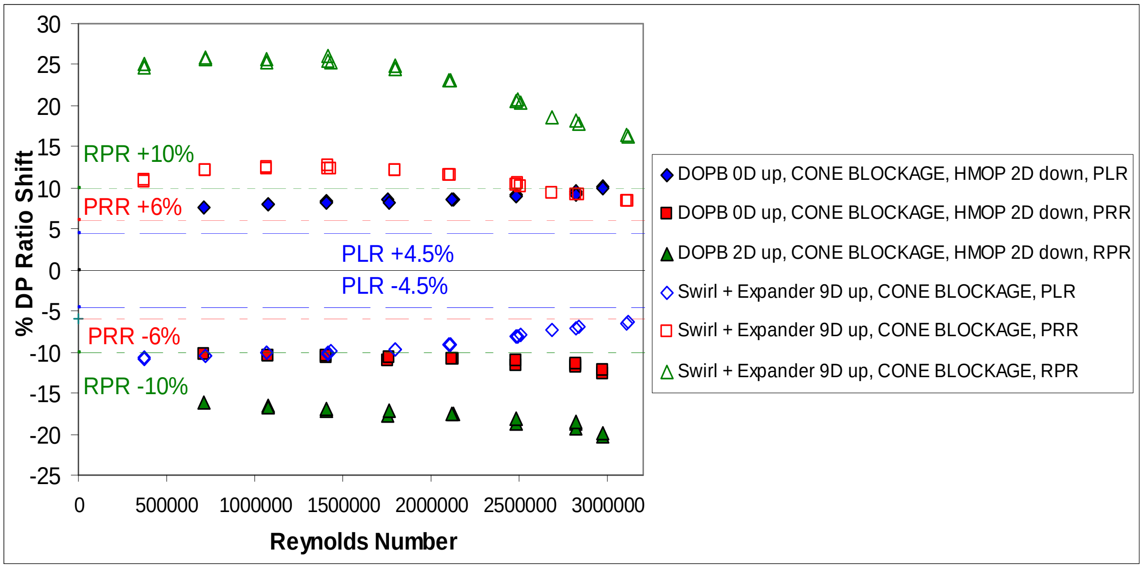

Fig 24. 4", 0.63 beta cone meter DP ratio results with trapped nut in two installations.

that there can be different sensitivities in the two ways of comparing a pair of DP's and therefore it is preferable to use both together. In this case the diagnostic alarm would have noticed that the meter was not operating correctly. That is, the meter output with the +5% and +8% errors from the two installations with the trapped nut at the cone assembly would have been noted as suspect results by the diagnostic system. Note that this blockage is in fact relatively small and the diagnostic system still clearly sees a problem.

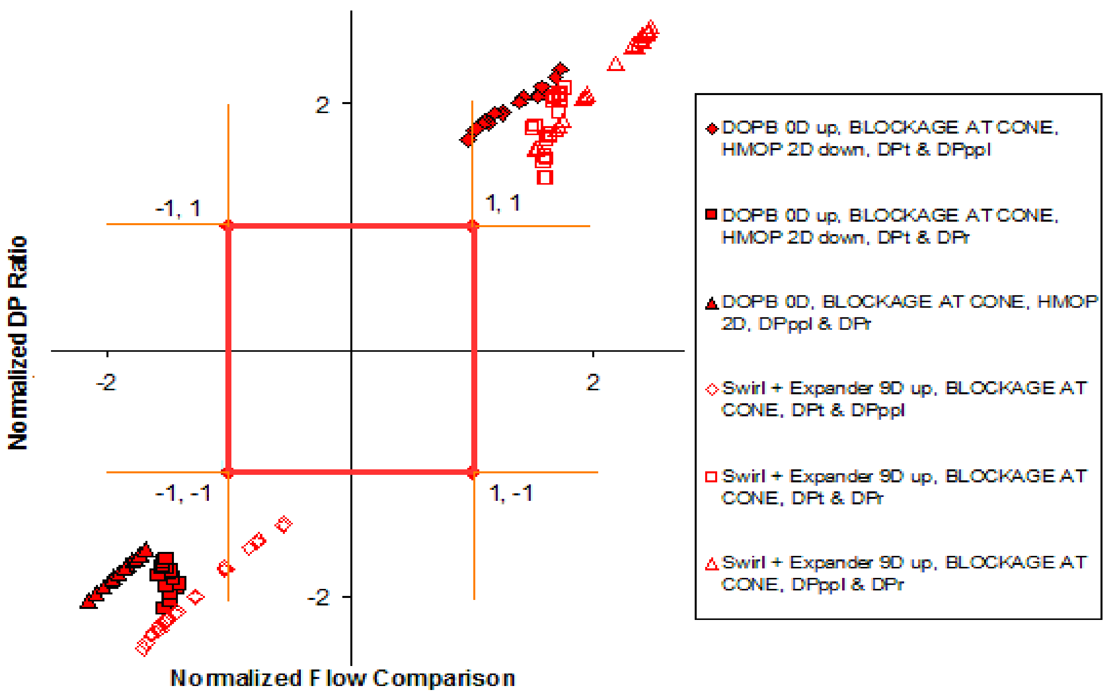

Fig 25. 4", 0.63 beta cone DP meter results with trapped nut in two installations.

4b. ΔP Cone Meter Performance with DP Transmitter Problems

DP meters are reliant on DP transmitters. Modern transmitters have DP turn downs of up to 100:1 (depending on transmitter type, flow conditions and the allowable uncertainty). This allows flow rate turndowns of up to 10:1 without stacking transmitters. Most DP transmitters are extremely reliable. However, they are not infallible. Incorrect DP readings result in incorrect flow rate predictions.

There are several common DP transmitter problems. One problem is exceeding their maximum range (or "**U**pper **R**ange **L**imit", URL) where the transmitter is said to be saturated. Another problem is use below the minimum advisable limit where the DP uncertainty significantly increases. Another problem is use with incorrect calibration information (due to incorrect calibration input, transmitter drift, etc.). Yet another problem is use with gas flow where the impulse lines are unevenly filled with liquid or one line is blocked. The diagnostic system can indicate metering problems caused by DP transmitter problems. The following is a theoretical diagnostic example of when the 4", 0.63 beta ratio ΔP Cone Meter discussed in section 3 has a saturated DP transmitter. In this example, the meter calibration will be accepted as the meters performance. Let us consider a flow through this meter at the following conditions:

Mass flow of 5.35 kg/s, pressure of 17.3 Bara, gas density of 20.76 kg/m^3, Reynolds number of 3,774,000 and an isentropic exponent of 1.3. Say the system uses a 400"WC URL transmitter for the traditional DP and 250"WC URL transmitter for the PPL. Say this particular system does not measure the recovered DP directly but calculates it by equation 1. Equation 2 predicts that the actual traditional DP as 432"WC meaning the actual DP exceeds the transmitters URL by 32"WC. A saturated transmitter reads the URL so the read DP is 400"WC. As the meters actual PLR is 0.559 the PPL is 241"WC. This value is within the 250"WC DP transmitters range. (Note that the diagnostic method works regardless of whether this is so or not. If both transmitters saturate the stated PLR is calculated falsely as 0.625, i.e. an 11.8% shift from the calibration value, thereby exceeding the allowable 4.5% threshold, a value of 2.6 on the ordinate of the normalized diagnostic box.) The actual recovered DP is therefore 191"WC but due to the saturated transmitter this system calculates it incorrect as 159"WC. The resulting traditional meter flow prediction is 5.16 kg/s, i.e. a -3.6% error. Traditional meters have no diagnostics to indicate that this error exists. However, applying the DP Diagnostics diagnostic methods gives a clear indication of a problem. For this situation the six diagnostic parameters produce the three points relative to this calibrated meters normalized diagnostic box, as shown in Figure 26.

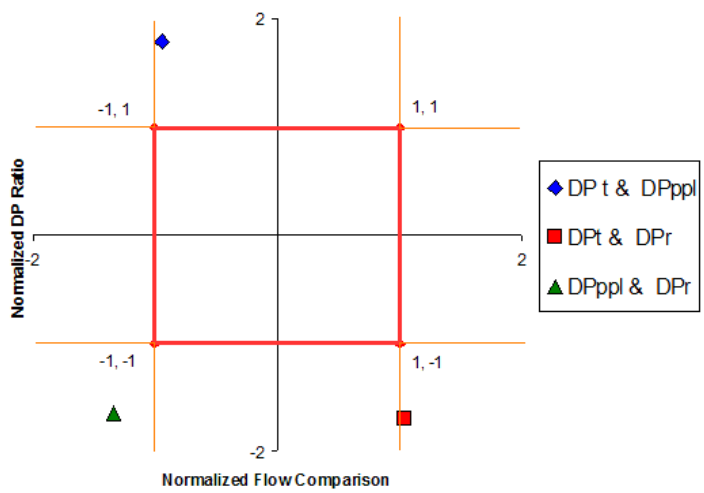

Fig 26. 4", 0.63 beta cone DP meter with a saturated DP transmitter.

Figure 27 shows the diagnostic analysis of actual data taken from the 4", 0.63 beta ratio cone DP meter during the baseline calibration when the DP's were deliberately dropped too low for the DP transmitters in use. The traditional and PPL DP transmitters both had URL's of 400"WC meaning that the absolute minimum DP the transmitters could be claimed to measure reliably was 4"WC. Similarly, the recovered DP's transmitter had an URL of 150"WC meaning the absolute minimum DP the transmitters could be claimed to measure reliably was 2"WC. Note, that the although a DP transmitter turndown is approximated by different manufacturers and users as somewhere between 50:1 and 100:1, a general rule is all DP's measured less than 2"WC are unreliable. As such CEESI, where these DP Diagnostic tests were conducted, limits most calibration data to minimum of 10"WC. In Figure 27 the deliberately low DP's of the two

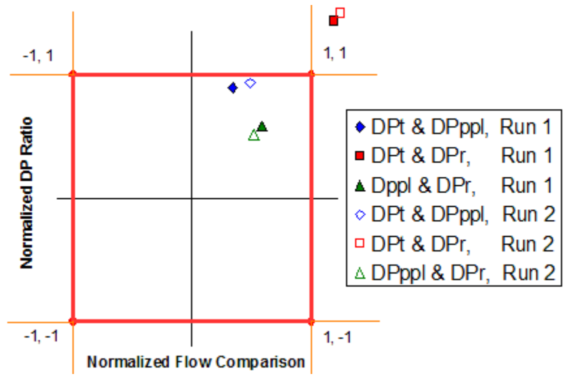

Fig 27. 4”, 0.63 beta cone DP meter with DP’s below the DP transmitter minimum limits.

repeat runs were approximately 3.7”WC for the traditional DP, 2.2”WC for the PPL and 1.8”WC for the recovered DP. Therefore, the traditional DP is just below the 100:1 DP turndown and significantly below the calibration labs cut off point. The PPL is below both minimum limits as is the recovered DP. ***Naturally, these points were disregarded by CEESI during the calibration procedure***. That is, these points were not used in this meters calibration.

In this real example the actual traditional flow calculation happened to still operated correctly. The traditional meter gave both runs mass flow rates to approximately -0.4%. However, this is by luck, rather than by design. The traditional DP reading has a large uncertainty band. It could just as easily have predicted a flow rate outside the stated 0.5% uncertainty of the meter. The PPL equation also gave the flow to (just) within the calibrated uncertainty. However, the expansion meter utilizing the recovered DP (the lowest value of the DP’s measured) gave a flow rate that was approximately +3.8%, i.e. well outside the calibrated ±1.1% uncertainty. Furthermore the PLR and RPR were within the calibrated uncertainty but the PRR was not. The result of the diagnostics shown in Figure 27 is that an alarm is set for this condition.

The traditional meter has given the correct flow rate but yet the diagnostics show a problem. Is this then a false alarm? This is a matter of opinion. Here the traditional meter is being used outside its turndown specifications and in this situation flow rate prediction errors can and do happen in many such situations. When a DP drops below the minimum DP limit for a transmitter, the DP meter is being supplied an unreliable DP and hence the meter is really “guesstimating” the flow rate instead of metering it. The meters uncertainty rating is therefore not valid in this condition. It just so happens that in this example by luck, the meter flow rate prediction was correct. However, in many real world low DP situations the operator doesn’t know if the meter is working within its stated uncertainty or not, and often it isn’t. The expansion and PPL equations are more susceptible to low DP’s as their DP’s are always lower then the traditional DP (see equation 1). Hence one of these flow equations will show a low DP problem first, before the traditional meter does. Therefore, the diagnostic system indicates when the DP’s are becoming so low that a potential metering problem is present. A general useful guide for DP meter users to use is that they ***shall*** not saturate the DP transmitters as this can causes gross errors and they ***should*** not drop the DP’s below the transmitters minimum limits as this increases the flow rate prediction uncertainty.

4c. <u>ΔP Cone Meter Performance with Physical Damage to the Cone Assembly</u>

Physical damage to the wetted components cause flow rate prediction errors. If a non-gusseted cone DP meter (common at ≤ 6” diameter) is dropped or heavily bumped during transportation or installation, or struck in service by a pressure spike or slug, the shock loading on the cone assembly can cause plastic deformation. Furthermore, any ***very substantial*** over speed of the system beyond the design limits can apply a drag force on the cone assembly enough to cause plastic deformation.

The theoretical design of cone DP meters has the cone and meter body aligned. In reality manufacturing tolerances mean that the cone usually has a small deviation from the center line. It is up to the skill of the manufacturer to assure this deviation is very small, but it is unreasonable not to expect very small deviations, even in a well built meter. DP Diagnostics built a wafer style (i.e. flangeless) 4”, schedule 80,

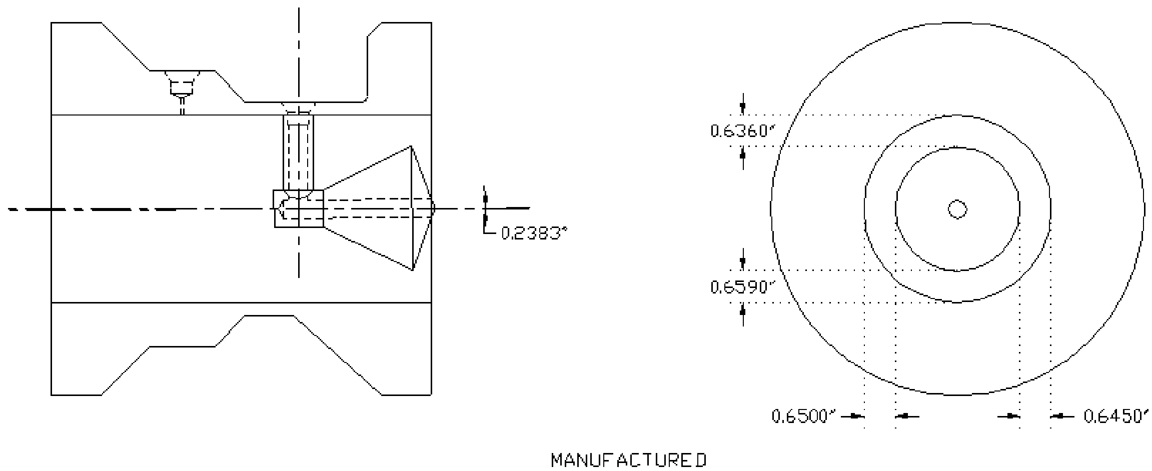

Fig 28. Sketch of the actual 4", 0.75 beta ratio cone DP meter built.

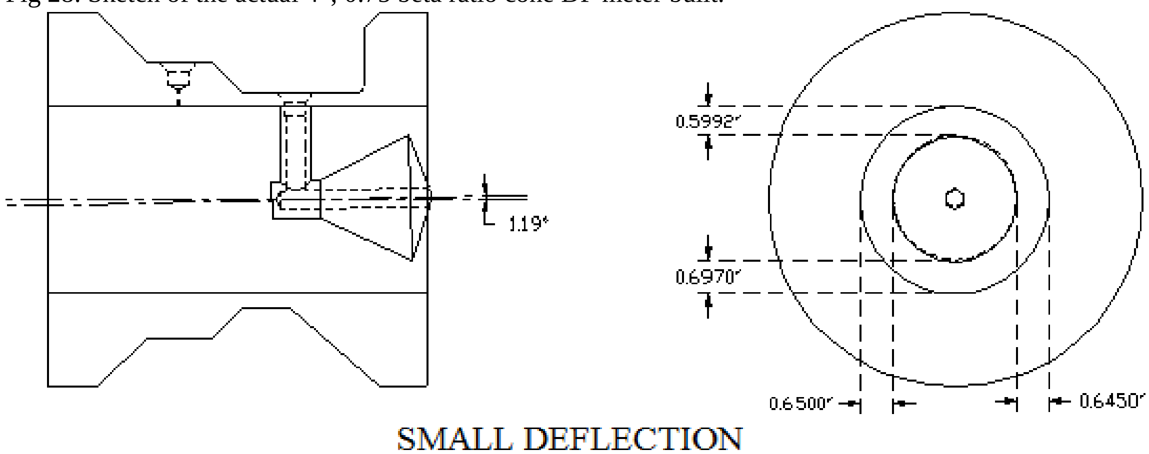

Fig 28a. Sketch of very mild damage to 4", 0.75 beta ratio cone DP meter.

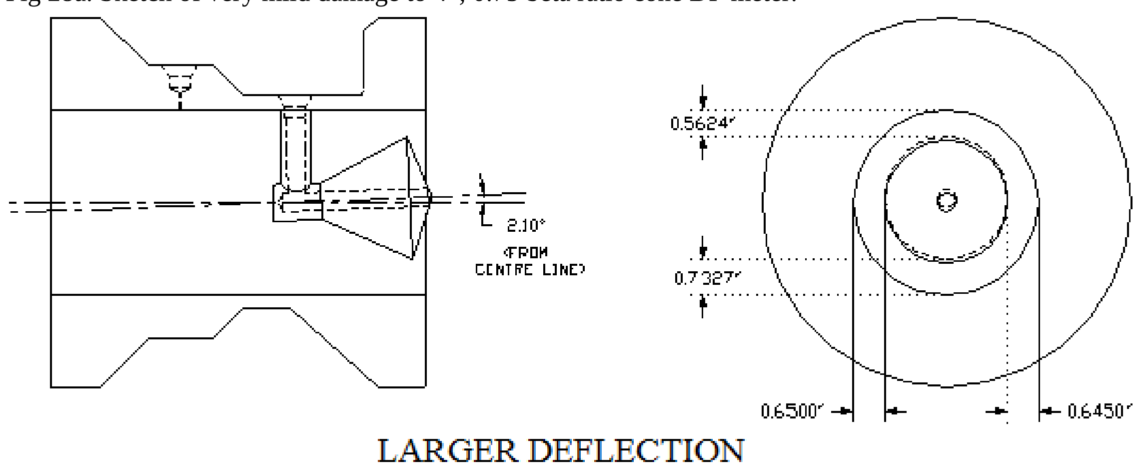

Fig 28b. Sketch of the moderate damaged 4", 0.75 beta ratio cone DP meter.

0.75 beta ratio ΔP Cone Meter. The actual cone to body centerline deviation measured after manufacture is shown in Figure 28. It is 0.238^0. This is as small a deviation as is practical for mass production techniques. This meter was calibrated at CEESI with long straight length upstream and downstream runs. The flow coefficient and pressure ratio calibration is shown in Figures 29 & 30 respectively. (Note that the downstream tapping was located in the downstream spool.) For simplicity here, the baseline calibration parameter values are set as constants (although further improved performance is available by fitting the

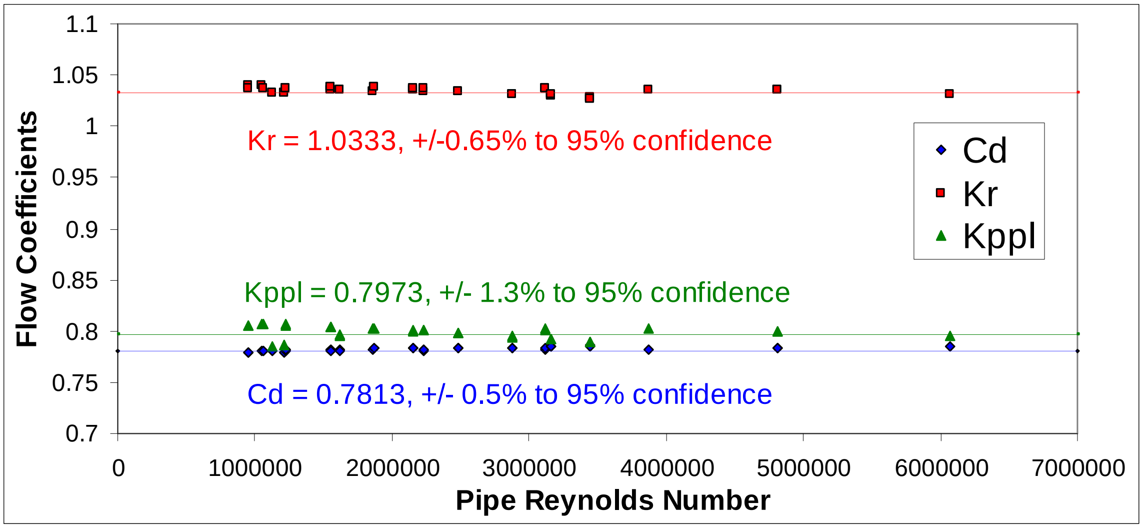

Fig 29. 4", 0.75 beta ratio, wafer ΔP cone meter baseline flow coefficient results.

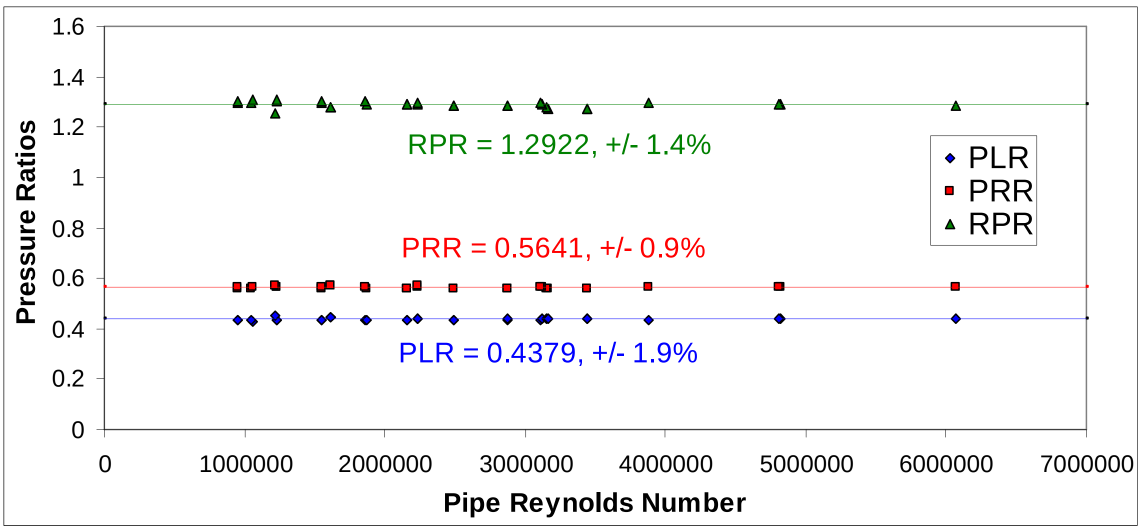

Fig 30. 4", 0.75 beta ratio, wafer ΔP cone meter baseline DP ratio results.

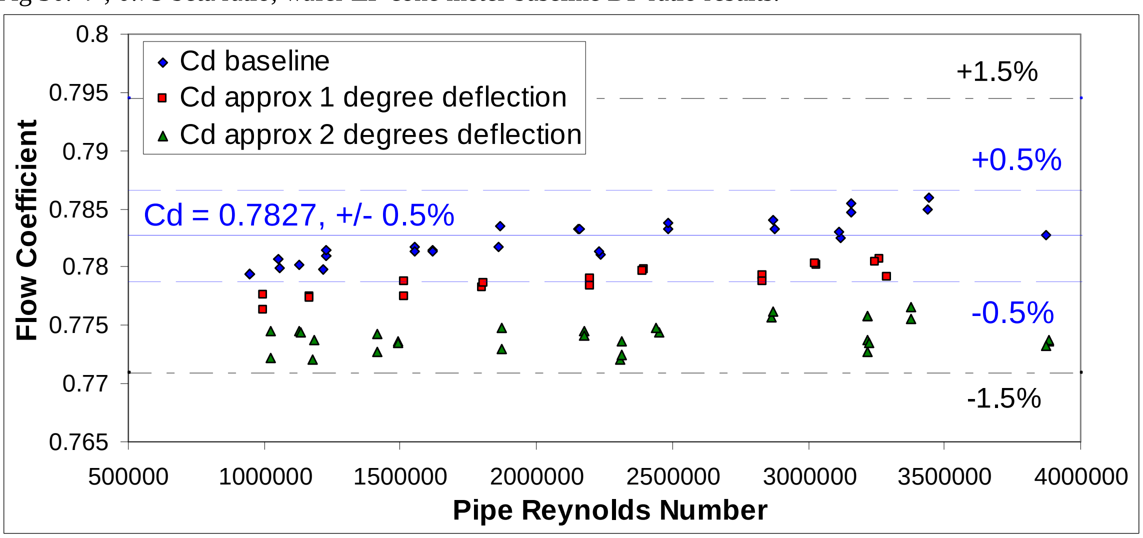

Fig 31. 4", 0.75 beta ratio, cone meter discharge coefficient variation with deflection.

data to the Reynolds number). These values have similar magnitude baseline uncertainties to the 4", 0.63 beta ratio cone meter discussed above.

Figures 28a & 28b show the cone deflection applied to simulate actual mild field damage. The initial 0.24^0 manufactured misalignment between centre line of the meter body and cone was increased to 1.19^0 and then 2.10^0. The meter was calibrated as manufactured. Figure 31 shows the discharge coefficient shift as the meter is damaged. An approximate shift of 1^0 caused the meter to over-read by approximately 0.4%. An approximate shift of 2^0 caused the meter to over-read by approximately 1.2%.

In actual application this meter may encounter asymmetric and swirling flow from a typical cone DP meter installation. As the earlier meter was tested installed in some of the most extreme real world conditions it is therefore reasonable to apply the same expanded uncertainties to these six calibration parameters as was done to the earlier tested meter. These uncertainties are shown in Table 2.

C_d	K_r	K_{PPL}	PLR	PRR	RPR	$\phi\%$	$\xi\%$	$\upsilon\%$
±1%	±2.5%	±2.5%	±4.5%	±6%	±10%	±3.5%	±3.5%	±5%

Table 2. Set uncertainties of the 4", 0.75 beta ratio wafer type cone DP meter.

Figure 32 shows the results of plotting all the data on the normalized diagnostic box. The calibrated data of course clusters closely around the origin well inside the box. The 1.19^0 cone deflection data is further spread out from the origin of the graph than the baseline data, but it is still well inside the allowable variation limits. The 1.19^0 cone deflection data showed a performance shift of about 0.4% (see Figure 31) but this is too small a shift for the sensitivity of the diagnostic system which operates by comparing differences. This then is beyond the capability of the diagnostic system. However, the 2.1^0 cone deflection data showed a performance shift of about 1.2% (see Figure 31) and the diagnostic data is spread out from the origin to a much larger extent than the other data sets. In fact the traditional DP and PPL data comparison triggers the alarm. Again, the DP ratio data is more sensitive than the flow rate comparisons. The majority of the DP ratio indicates a problem and the flow rate comparison does not. This indicates to the operator a problem likely exists but it is a relatively small problem. In fact here we see the error is in the order of 1.2%. Therefore, the diagnostic system can see relatively small metering problems caused by primary element damage. Obviously, more significant damage would be far more easily seen by this DP Diagnostics diagnostic system.

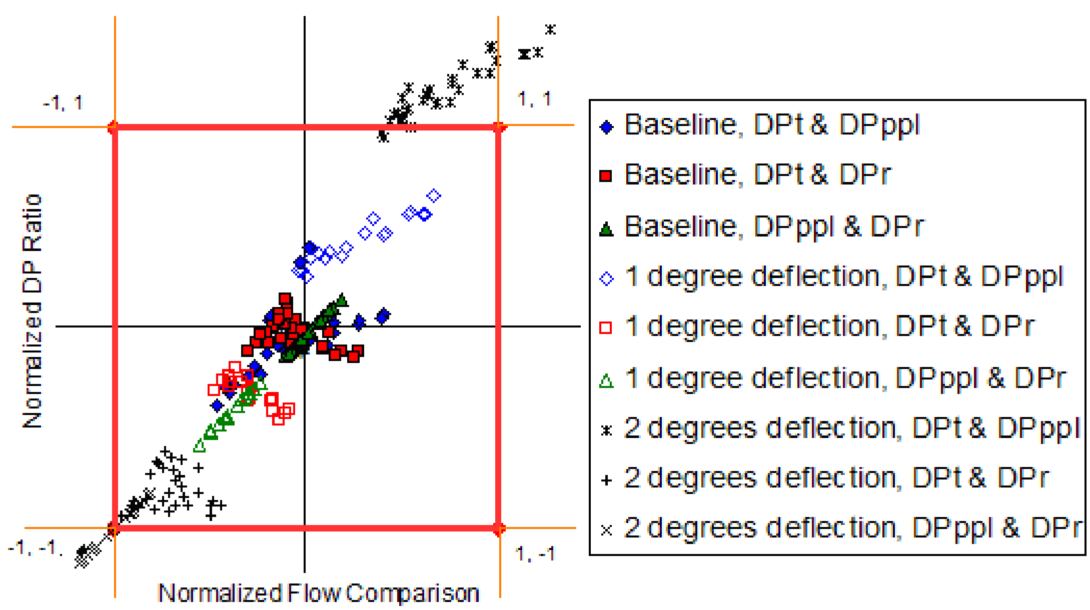

Fig 32. Normalized diagnostic box for as manufactured and after damage performance.

Conclusions

The cone DP meter is known to be resistant to flow disturbances. However, DP Diagnostics investigated this resistance to some of the most extreme installations possible. The meter was shown to be very resistant to most of these installations but not completely immune to them all. Pipe bends before and after the meter, or downstream valves or upstream valves installed further than 7D, had no appreciable affect on the meters performance. However, it was found that it was advisable to not install a valve within 7D upstream of a cone DP meter or have a flow expansion less than 9D upstream of the meter if the flow has already got excessive swirl. It should be noted that these two cautionary installations are very rare and as extreme an installation as any meter could reasonably expect to experience. Furthermore, the cone DP meter continued to operate in these installations with only small biases applied to the flow rate predictions. Hence, the cone DP meter proved itself to be exceptionally resistant to most real world flow disturbances.

The DP Diagnostics diagnostic methods are simple but effective. The diagnostic methods were shown to be of great practical use even when the cone DP meter is experiencing significant flow disturbances. The two different methods of comparing DP pairs both work well for serious meter problems (i.e. if the traditional meter flow prediction is in error by greater the 2%). As the DP ratio technique is seen to be more sensitive than the direct flow rate prediction comparison technique it can typically see smaller metering problems (sometimes with flow prediction errors less than 2%). Thus, with the diagnostic method being qualitative and not quantitative, it can be beneficial to apply both methods simultaneously. If the DP ratio comparison technique indicates a problem but the flow rate prediction comparison does not, then the problem is likely to be a small problem (or very rarely a false alarm) and an "amber alarm" or operator warning can be triggered. However, if both techniques state a problem it is likely to be a significant problem and a general alarm can be triggered.

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2. International Standard Organization, "Measurement of Fluid Flow by Means of Pressure Differential Devices, Inserted in circular cross section conduits running full", no. 5167.