CONE METERS FOR LIQUID AND GAS MEASUREMENT
Class # 8210

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1. Introduction

Differential Pressure (DP) meters have been used extensively since Herschel invented the Venturi meter, i.e. the original DP meter, in the 1880's. Since then there have been many different variants of DP meter appearing on the market. One of the most recent is the cone meter. The cone meter is a generic DP meter and uses the same generic DP meter flow equation as all other DP meters. All DP meter types exist on the market as they offer some advantage over the others. If a meter does not have some niche, whether it be reduced uncertainty, more reliability, wider range ability, self diagnostic capable or simply an attractive price, it would not be successful on the market. The cone meter has been steadily growing in market share for twenty years. Originally a patented device the patent expired several years ago and now the meter is a generic type offered by several suppliers.

The cone meter has some particular useful advantages over other meters. While giving the same flow rate uncertainty as other generic DP meters the cone meter has the very unusual characteristic of being extremely immune to upstream disturbances. Unlike most other flow meters the cone meter continues to predict the correct flow rate when the flow into the meter is disturbed by upstream flow components. The cone meter is not completely immune to being affected by flow disturbances, but it is far less sensitive to flow disturbances than most other meter types, both DP and non-DP meter designs. Therefore, while other meters require that for various upstream disturbances the meter shall have a certain upstream pipe run length and perhaps a flow conditioner, the cone meter typically does not need any upstream length, or at least requires vastly reduced straight pipe length requirements compared to other meters. This makes the meter ideal to the many applications in industry where space is scarce and significant straight pipe runs are not available.

Apart from the advantage of the reduced pipe work length requirements the cone meter can be attractive to industry as a standard generic DP meter. Venturi meters are usually chosen as they are very sturdy and offer minimal total pressure loss for an intrusive meter. Venturi meters are relatively expensive and require calibration. Therefore, compared to other DP meter designs Venturi meters have a relatively high CAPX but relatively low OPEX. On the other hand the orifice plate meter is seen a much less sturdy and creates a very significant total pressure loss. Orifice plate meters do not require calibration. Orifice meters can have a relatively low CAPX but a relatively high OPEX. However, the cone meter falls between the Venturi and cone meter in most of these specifications. The cone meter is far sturdier than the orifice meter although not as sturdy as the Venturi meter. The total pressure loss of a cone meter is between that of a Venturi and orifice plate meter. A cone meter is usually reasonably priced compared to a Venturi meter but (unless an orifice plate dual chamber is used) is more expensive than the orifice plate meter. Cone meters must be calibrated like the Venturi meter. Therefore, compared to other DP meter designs the cone meter tends to have a moderate CAPX and moderate OPEX. Often this fits the applications needs.

The cone meters patent has only relatively recently lapsed. Due to this fact there is not enough independent data available for any standards committees (e.g. API or ISO) to have written a cone meter standard. Therefore, there is no standards stated meter performance. Each cone meter must be calibrated to assure the correct discharge coefficient is being used for that meter. Once calibrated, cone meters are excellent reliable flow meters.

2. The Operating Principles of Cone Meters

A cone meter is a generic DP meter just like a Venturi meter. The cone meter gets its name from the shape of the primary element. The primary element is the physical obstruction used to accelerate the flow and cause the differential pressure. The design of the primary element is what makes the difference between DP meters. A Venturi meter has a converging section, a throat and a diffuser as a primary element. An orifice meter has a plate with a central hole installed perpendicular with the pipe centre line as a primary element. A cone meter has a cone installed in line with the pipe centre line with the cone pointing upstream and attached upstream at the cone apex by a circular support bar. There is a pressure port upstream of this cone assembly. Most cone meters have the low pressure port running from the centre of the back face of the cone through the cones centre line and up through the centre of the support bar. (A few cone meters have the low pressure read at the wall behind the cone. These are relatively rare and this paper does not discuss this rarer design.) Traditionally, the distance between the resulting inlet and low pressure port couplings is normally 2 1/8" to couple directly to a DP transmitter. This however is not a critical geometry. Figure 1 shows a drawing of a cone meter with cut away of the wall to expose the cone assembly. Figure 2 shows a sketch of a cone meter with named components and an indication of the flow profile.

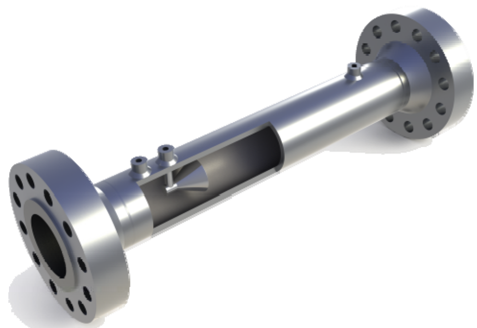

Figure 1. A drawing of a cone meter with cut away of the wall to expose the cone assembly.

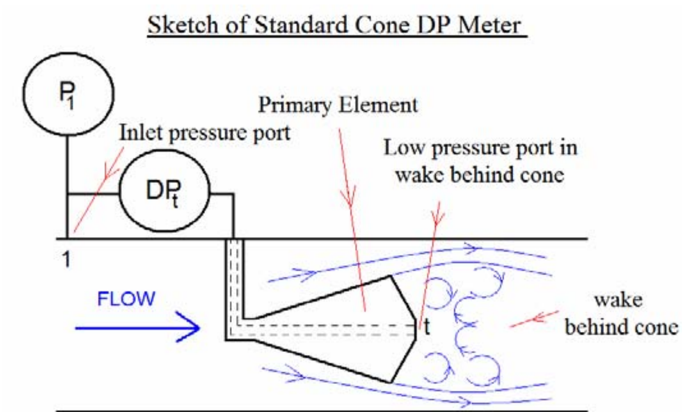

Figure 2. A sketch of a cone meter.

With the low pressure port located at the back of the cone the low pressure is reading the pressure in the cones "wake". A wake is a highly turbulent area of flow directly behind bodies immersed in a fluid flow. It is characterized by having strong vortices and low pressures. The use of a pressure reading away from the fluid stream often causes confusion but it should not. The cone meter is not the first DP meter to read at least one of the two pressures in a re-circulating section of the flow. In fact the orifice plate meter, which is one of the most widely used meters, also does this. It measures pressure at a re-circulating zone. Figure 3 shows how this well accepted DP meter measures both upstream and downstream pressures not in the free stream but in re-circulation zones. It does not matter to the operation of a DP meter. Note in Figure 3 that

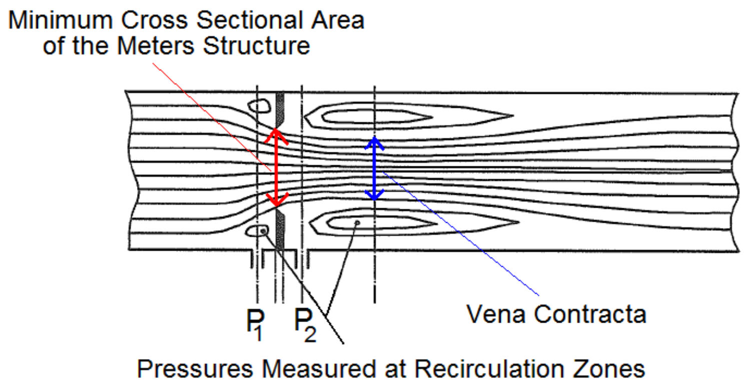

Figure 3. A sketch of an orifice plate meter reading high and low pressure in recirculation zones.

the flow passes the orifice and continues to reduce in area to a vena contracta. This is analogous with the flow area as it passes the cone in a cone meter, as sketched in Figure 4. The same generic flow equation is universal for all standard DP meter designs. That is the cone meter uses the same generic flow equation as all other DP meters (such as the Venturi meter, orifice meter, nozzle meter, wedge meter etc.).

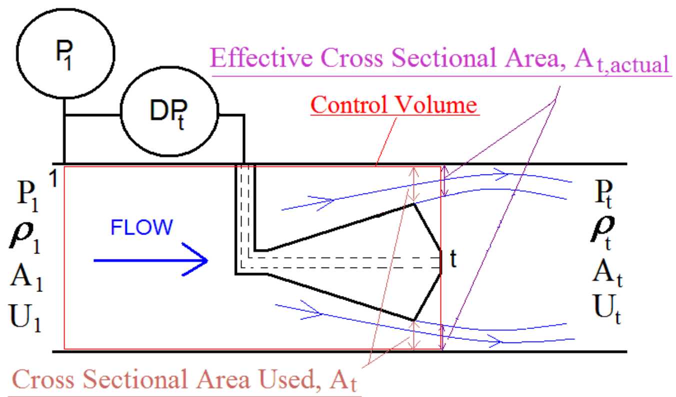

Figure 4. A sketch of a cone meter with a control volume drawn around the system.

Figure 4 shows a sketch of a cone meter with a control volume placed around the system. Note that, P is the pressure, U represents fluid velocity, ρ represents fluid density and A represents cross sectional area. The subscript "1" represents conditions at the meter inlet (where the upstream pressure port is located). The subscript "t" represents conditions at the control system outlet (where the upstream pressure port is located).

Consider incompressible flow (i.e. flow where the fluid density is constant) between the inlet to the meter (say section "1") and the cross sectional plane where the low pressure is read from (section "t"). Conservation of mass and energy exist across these planes (if we make the simplifying assumption of there being no energy losses). Notice that as the fluid moves past the edge of the cone it detaches from the cone and forms an annular jet downstream of the cone. The effective cross sectional area of this jet at the downstream side of the control volume is denoted in Figure 4 as $A_{t,actual}$. Directly behind the cone is the wake where the fluid is re-circulating. The actual mass flow downstream is in the fluid jet. The correct downstream cross sectional area to use in the flow calculation is the effective cross sectional area, $A_{t,actual}$. However, as this area is not known (and in fact changes with flow rate) the known annular area between the cone edge and the wall (denoted as A_t) is used.

The mass and energy conservation equations can be applied for a horizontal incompressible flow (equations 1 & 2). Note that m is the mass flow rate. Equations 1 & 2 can be re-arranged into equations 1a & 2a respectively.

$$\dot{m} = \rho A_1 U_1 = \rho A_t U_t \quad \text{--- (1)} \qquad \frac{P_1}{\rho} + \frac{U_1^2}{2} = \frac{P_t}{\rho} + \frac{U_t^2}{2} \quad \text{--- (2)}$$

$$\frac{A_t}{A_1} = \frac{U_1}{U_t} \quad \text{--- (1a)} \qquad \frac{\Delta P}{\rho} = \frac{P_1 - P_t}{\rho} = \frac{U_t^2}{2}\left(1 - \left(\frac{U_1}{U_t}\right)^2\right) \quad \text{--- (2a)}$$

Therefore substituting equation 1a into equation 2a gives equation 3 which can be rearranged to give equation 3a:

$$\frac{\Delta P}{\rho} = \frac{U_t^2}{2}\left(1 - \left(\frac{A_t}{A_1}\right)^2\right) \quad \text{--- (3)} \qquad U_t = \frac{1}{\sqrt{1-\left(A_t/A_1\right)^2}}\sqrt{\frac{2\Delta P}{\rho}} \quad \text{-- (3a)}$$

Substituting equation 3a into the equation 1 where the beta ratio β is defined as equation 5:

$$\dot{m} = \frac{\rho A_t}{\sqrt{1-\left(A_t/A_1\right)^2}}\sqrt{\frac{2\Delta P}{\rho}} = \frac{A_t}{\sqrt{1-\beta^4}}\sqrt{2\rho\Delta P} \quad \text{--- (4)} \qquad \beta = \sqrt{\frac{A_t}{A_1}} \quad \text{--- (5)}$$

It is convention with all DP meters to let the “velocity of approach”, E , be defined as equation 6. Therefore equation 4 can be expressed as equation 4a. :

$$E = 1\Big/\sqrt{1-\beta^4} \quad \text{--- (6)} \qquad \dot{m} = E A_t \sqrt{2\rho\Delta P} \quad \text{--- (4a)}$$

Equation 4a is the theoretical mass flow equation of all DP meters, not just the cone meter. The same equation can be derived regardless of the primary element design. Therefore, note that this is a generic DP meter flow equation. There is no fundamentally unique and special cone DP meter equation. The cone just uses the generic DP meter equation!

In reality the theoretical flow equation does not work for any DP meter, including the cone meter. There are certain simplifying assumptions in the theoretical flow equations development that are too simplistic and they need to be corrected for. At this point in the development of individual DP meter flow equations the correction factors are unique to the primary element chosen. For the case of the cone meter there are three issues regarding equation 4a. The first is that the cross sectional area of the effective flow in the jet ($A_{t,actual}$ in Figure 4) is not known so the equation uses the slightly different known geometry of the cross sectional area between the cone edge and the pipe wall (i.e. A_t in Figure 4). A correction is required to correct for this inaccuracy. Furthermore, the assumption of no energy losses is obviously not true. This must also be corrected for. The third issue is with the assumption of incompressibility. Liquids are effectively incompressible and therefore for liquid flow this assumption is valid. However, gas is highly compressible and therefore for gas flows this assumption is invalid. Therefore gas flow applications require a gas density correction whereas liquid flow applications do not.

None of the three required correction factors can be theoretically derived. Hence, they can be lumped together to create a single correction factor or “flow coefficient”, denoted by “K”. However, if the flow is a gas the gas correction factor, called an expansion factor denoted by Y, can be separated out. The combined correction for the area and energy loss assumptions only is called the discharge coefficient and denoted by “Cd”. Note as liquid is incompressible then for all liquids Y is unity, and therefore for liquid flows only the discharge coefficient and the flow coefficient are the same thing. The flow coefficient and the discharge coefficient for cone meters have the same definition as all DP meters. They are defined by equation 7. Note that m_{actual} and m_{theory}

represent the actual mass flow being measured and the mass flow rate being predicted by the theoretical equation 4a. The cone meter expansion factor is shown as equation 8. The derivation of this equation is well beyond the scope of this paper but interested readers will find the derivation published by Stewart [1]. The cone meter expansion factor is unique to the cone meter. All DP meter types have a unique expansion factor but these equations contain the same variables. Note that κ is the fluid property called the isentropic exponent. This is usually easily available from look up tables for most common fluids. It does not change much for a given fluid across wide ranges of thermodynamic conditions so this value usually gets entered as a constant value by keypad to the flow computer. Equation 9 then shows the cone meter gas flow rate equation. The expansion factor disappears from the equation for liquid flows. Therefore equation 9a shows the cone meter liquid flow rate equation. Note that in equations 9 & 9a the subscript actual“” has been dropped and replaced with “g” & “l” respectively to denote the predicted gas and predicted liquid flows respectively.

$$K = YC_d = \dot{m}_{actual} \Big/ \dot{m}_{theory} \quad \text{-- (7)}$$

$$Y = 1 - \left(\left(0.649 + \left(0.696\beta^4\right)\right)\left(\Delta P / \kappa P\right)\right) \quad \text{-- (8)}$$

For gas: $$\dot{m}_g = EA_t Y C_d \sqrt{2\rho \Delta P} \quad \text{---(9)}$$

For liquid: $$\dot{m}_l = EA_t C_d \sqrt{2\rho \Delta P} \quad \text{--(9a)}$$

Equations 9 & 9a for gas and liquid flows through cone meters are still not unique to the cone meter. These are still generic DP meter flow rate equations. The difference between the DP meters is simply what expression is used for the discharge coefficient and the expansion factor. As the expansion factor is known (equation 8) the unknown now is the discharge coefficient. It is well known that the approximate cone meter discharge coefficient is 0.8. This compares to an approximate orifice meter discharge coefficient of 0.6 and an approximate Venturi meter discharge coefficient of 0.995.

3. Cone Meter Calibration

For a cone meter the discharge coefficient is found by calibration. Note that most generic DP meters have their discharge coefficient found by calibration. A notable exception is the orifice meter. API / ISO orifice meter standards cover a huge flow range and predict the discharge coefficient for set geometry orifice meters. This is somewhat true of Venturi but the API / ISO standards only have limited flow ranges for this meter where the discharge coefficients are predicted. Therefore, in most gas flow applications at least (and some liquid flow applications) Venturi meters also need to be calibrated to find their discharge coefficient. Therefore Venturi meters and cone meters are similar in this regard.

$$C_d = \frac{\dot{m}_{reference}}{\dot{m}_{theory}} = \frac{\dot{m}_{reference}}{EA_t\sqrt{2\rho\Delta P}} \quad \text{--- (10)}$$

$$\mathrm{Re} = \frac{\rho U D}{\mu} = \frac{4\dot{m}}{\pi \mu D} \quad \text{--- (11)}$$

Cone meters should be tested or “calibrated” under the full flow rate range of the application they are destined for, in a test facility where the “actual” mass flow rate is recorded by a reference meter of stated low uncertainty. Then, the flow coefficient can be found by equation 10. It is a fact of DP meter performance that the Reynolds number is the important factor in determining the variation of the coefficient across the flow range. For cone meters (like all DP meters) the discharge coefficient may not be constant across a large turn down (i.e. flow range). The discharge coefficient is often sensitive to the Reynolds number. This is shown as equation 11, where μ is the fluid viscosity, U is the average fluid velocity and D is the pipe diameter.

Figure 5 shows a real CEESI gas flow rate calibration of a 4”, 0.75 beta ratio cone meter. Note that the calibration procedure is to plot the discharge coefficient to the Reynolds number and then fit an equation relating the two parameters. In this case the equation was a linear line and across

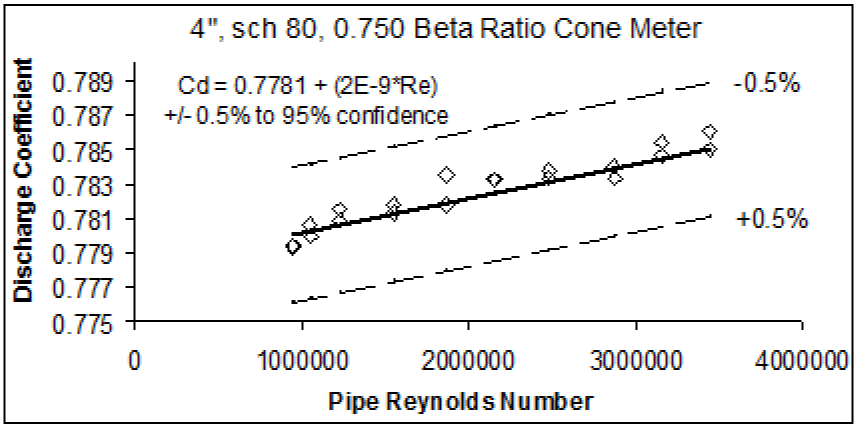

Figure 5. A gas flow calibration result for a 4", 0.75 beta ratio cone meter.

the range of the calibration the fit predicted the discharge coefficient well within ±0.5% of the test data. This is the typical uncertainty of a **calibrated** cone meter. Without calibration over the full Reynolds number range of the application, it has been shown by Hodges et al [2] that an estimated discharge coefficient has an uncertainty of up to ±8%. It is important then to calibrate a cone meter. A properly calibrated cone meter predicts the flow rate up to <0.5%.

$$C_d = f(\mathrm{Re}) = f\left(\dot{m}/\pi\mu D\right) \quad \text{--(12)} \qquad \dot{m} - \left\{EA_tY * f\left(\dot{m}/\pi\mu D\right) * \sqrt{2\rho\Delta P}\right\} = 0 \quad \text{--(9b)}$$

Equation 12 shows the generic form of the discharge coefficient to Reynolds number fit. It should be noted that there is no restriction on the form of the function "f", i.e. the type of equation used to fit the data. Occasionally the discharge coefficient is insensitive enough to the Reynolds number to allow a constant discharge coefficient to give the required flow rate prediction uncertainty. However, more complicated equations generally give better results. Note though that the more complicated the equation the more chance of "over-fitting" the data – which means the equation is fitted so closely to the data it also accounts for some of the test data's random scatter and uncertainties. In such a case a false low uncertainty value can be claimed. The simplest possible equation should be used to fit data.

Note that the Reynolds number is related to the mass flow rate. This is the parameter the meter is measuring. Hence the answer must be known to find the answer. However, it's one equation and one unknown, so this of course means that the cone DP meter flow rate prediction is produced from an iteration as shown by equation 9b. A typical iteration start point to avoid divergence is the mass flow rate that gives a discharge coefficient of 0.8.

4. Cone DP Meter Performance and Calibration Issues

Although the cone DP meter has no standard it is known from experience that the cone DP meter discharge coefficient is approximately 0.8. However, it is also known from experience that this can vary between individual meters by ±8%, as discussed by Hodges et al [2]. This can be due to several reasons such as the relative size of the support bars changing between meters, slightly different cone designs (due to manufacturing considerations for different diameter meters) and deliberately liberal manufacturing tolerances to ease manufacturing complexity. The manufacturers can allow this as they typically state that each cone DP meter should be calibrated across the full Reynolds number range of the application. It is stated by the manufacturers that ***if each cone DP meter is properly calibrated*** the meter has "***up to*** 0.5% uncertainty".

It is a performance fact of DP meters that, as long as the expansibility is accounted for, it does not matter what fluid is used to calibrate the meter (as long as the fluid is Newtonian). Therefore, a natural gas cone meter can be calibrated in an air flow calibration facility or a gas cone meter can be calibrated with a water flow calibration facility etc.. <u>The single, but critical, stipulation is that the Reynolds number range of the application is met</u>. If this stipulation is met, a DP meter calibration carried out with one fluid is applicable to when the meter is in use with any other fluid.

Water flow meter calibration facilities are simpler and less expensive to operate than gas flow meter calibration facilities. Therefore, calibrating a cone meter with a water flow can be attractive to both manufacturer and meter users. However, there can be a significant potential problem with this approach. This problem hinges on the fact that the Reynolds number range of the application must be met. Equation 11 shows that the Reynolds number is a function of the fluid density, average fluid velocity, the inlet diameter and the fluid viscosity. For a given meter the inlet diameter is of course set. However, if we consider a set velocity value we see that the Reynolds number is a function of the fluid density and viscosity. Liquids are considerably denser than gases (even at extremely high pressures) but gas is typically a couple of orders of magnitude less viscous than liquids. Hence, for any cone meter with a flow with a set average velocity, a liquid flow has a Reynolds number an order of magnitude less than a gas flow. The effect this has on cone meter calibration is that ***it is unlikely that a water calibration facility can reach the upper Reynolds number values required for many (if not most) gas flow metering applications***. Therefore, if water flow calibration data is used to find a cone meters discharge coefficient for a gas flow application, it is likely that only the lower end of the gas applications Reynolds number range will be reached even at the maximum capabilities of the water flow calibration facility. Where calibration data from liquid and gas facilities have matching Reynolds numbers the discharge coefficient will be the same. However, at higher gas flow application Reynolds numbers, where water flow test data must be extrapolated, the discharge coefficient is being estimated only. As cone meters often have a discharge coefficient vs. Reynolds number relationship that is not constant this extrapolation can lead to substantial metering errors.

If a cone meter is calibrated across the applications full Reynolds number range then the cone DP meter will be a reliable flow meter capable of giving flow rates to an uncertainty up to 0.5% across a 10:1 turndown[1]. The cone meter has no moving parts and therefore if properly calibrated and installed, and if it receives no damage, wear, trapped foreign objects or contamination issues, then the calibration result / meter performance will remain constant (as long as the instrumentation is properly maintained). However, failure to calibrate the cone meter correctly can lead to an increase in flow rate measurement uncertainty or a significant bias on the flow rate measurement. The following discussion discusses potential calibration issues with cone meters.

4a. <u>The Necessity for Calibration Across the Applications Full Reynolds Number Range</u>

If a cone meter is calibrated across a relatively low Reynolds number range (e.g. with water flow calibration facility) it is often not possible to see any discharge coefficient relationship with the Reynolds number over a larger turndown. As a result a low Reynolds number range / water calibration can give the illusion that the meters discharge coefficient is constant, and / or can suggest the performance at higher Reynolds numbers is different to what it actually is. Often calibration across a larger turndown (usually by means of gas flow tests) shows extrapolation of lower Reynolds number data to be incorrect. Hence, ***a cone DP meters uncertainty rating is only applicable within the Reynolds number range of its calibration***. Extrapolating a low Reynolds number calibration for use with high Reynolds number flows invalidates the uncertainty rating and may lead to significant bias in the flow measurement. An example is now given.

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[1] There is a debate about the flow rate turndown capability of DP meters. A traditional limit is a very modest 3:1. This corresponds to an approximate DP transmitter turndown of 9:1 (see equation 9). However, DP transmitters have improved considerably since this traditional DP meter limit was set many years ago. Modern DP transmitters typically give reliable DP turndowns between 50:1 and 100:1 which corresponds to DP meter flow rate turndowns between approximately 7:1 and 10:1. This can be further extended by stacking DP transmitters of different ranges. Naturally, the uncertainty of any DP transmitter increases at the lower end of its range. A DP meters turndown rating depends on the calibrated Reynolds number range as well as acceptably accurate DP readings.

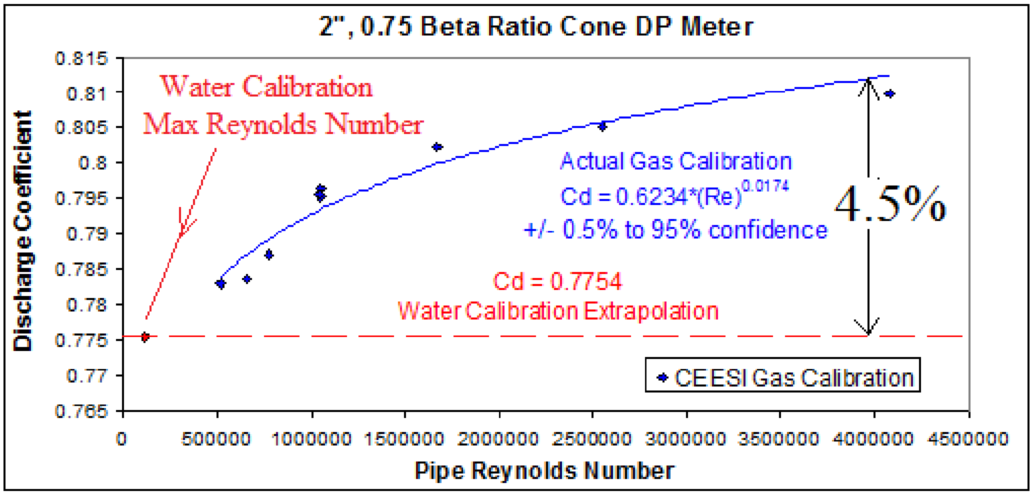

Figure 6. 2", 0.75 beta ratio cone meter water and gas calibration results.

A 2", 0.75 beta ratio cone meter was supplied to a gas flow application with a water calibration. The discharge coefficient was stated to be a set value of 0.7754 based on a water flow calibration which had a maximum Reynolds number of 114,606. During use at considerably higher Reynolds numbers a potential performance problem was noted. By plotting subsequent gas flow calibration data at Reynolds numbers up to 4e6 it was found that extrapolation of the water calibration data was causing a 4.5% under-reading of the gas flow rate. Data fitting all the data across the full Reynolds number range gave a meter uncertainty of 0.5% as required. Figure 2 shows these results. Note that the gas calibration can be done at any pressure. When calibrating a cone meter the Reynolds number range is the parameter range that matters, as long as the Reynolds number range is met the gas pressure / density does not matter. Hence, it is not good practice to extrapolate cone meter calibrations to higher Reynolds numbers. Such practice can induce significant measurement errors. Only when a cone meter is calibrated across the full Reynolds number range is the meters uncertainty statement meaningful. If a cone meter is calibrated across the full Reynolds number range of the application the meter usually gives ±0.5% at 95% confidence across a turndown of 10:1. If it is not calibrated across the full Reynolds number range the uncertainty in flow measurement is simply unknown outside the calibrated range.

4b. <u>The Necessity to Calibrate Each Individual Cone DP Meter</u>

Many flow meter applications are in systems where multiple identical meters are required. If multiple meters are ordered, which are on paper said to be identical, there is a temptation to calibrate one meter only and apply that calibration to all meters of that specification. The rational of this proposed approach is based on the assumption that because the meters are said to be identical their performance under the same flow conditions should also be identical. Therefore, this common argument is wholly based on the assumption that because the meters are identical on paper they are also identical in reality. However, in reality there are manufacturing tolerances. No two flow meters are truly identical. With the current typical cone meter manufacturing tolerances, although meters are identical on paper they can be subtly different in practice. As the manufacturers state each meter should be individually calibrated this is not in itself an issue. However, as it would be advantageous to not have to calibrate multiple meters of the same specification it is interesting to know what shifts in discharge coefficients are caused by the subtle differences between the *nominally* identical cone DP meters. Unfortunately there is little in the literature that describes the level of allowable geometric variation between nominally identical cone DP meters before they begin to have significantly different characteristics. Hence, at the time of writing, industry has no guarantee two cone DP meters built from the same drawing are in fact identical or have the same performance characteristics.

Let us consider two 4", schedule 80, 0.45 beta ratio cone meters that are identical on paper. They were built by the same manufacturer, at the same fabrication shop, from the same drawing.

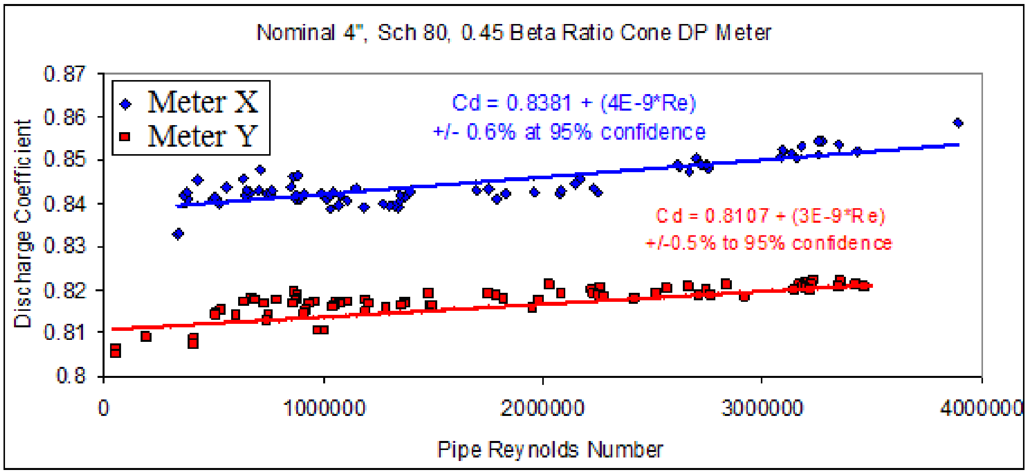

Figure 7. Comparison of two nominally identical cone DP meter calibrations.

However, it should be noted that the first meter (Meter X) had an ID of 3.812" and a beta ratio of 0.4512, whereas, the second meter (Meter Y) had an ID bore of 3.823" and a beta ratio of 0.4500. When the two meter calibrations were compared (see Figure 7) it was found that there was approximately 4% difference between the meters. Therefore, if only one of the meters were calibrated and the result assumed to be valid for the other nominally identical meter the un-calibrated meter would have a flow rate prediction bias of 4%. Therefore, it is not advisable to assign the result of one cone meter calibration to another cone meter even if the meters are nominally identical. The differences in the meters due to manufacturing tolerances can cause significant performance differences. Note, however that it is possible, depending on chance, that two nominally identical cone meters may have very similar performances. The chance of this seems to increase with larger meters. However, it can't be guaranteed that any two nominally identical meters have a similar performance until they are both calibrated. If each individual cone meter is calibrated across the full Reynolds number range of the application the meter usually gives ±0.5% at 95% confidence across a turndown of 10:1. However, assigning one meters calibration to another meter, even if they are nominally identical can result in significant metering errors.

4c. <u>A Discussion on the Requirement for Periodic Re-Calibration</u>

If nominally identical cone meters were <u>truly</u> identical their performance would be identical and only one meter out of a batch of identical meters would require calibration for the performance of all the meters to be found. This is because for a set geometry there is a set meter performance. For any given cone meter, as long as the geometry remains constant (i.e. there is no wear, contamination, cone deflection etc.), then the performance, i.e. the relationship between the Reynolds number and the discharge coefficient, is set.

Proof of this statement is given in Figure 8. Here three separate calibrations of the same cone meter are shown. The meter was periodically sent for re-calibration by the operator. Clearly, no significant difference is seen between the calibration results. The original 2004 calibration result is still valid in 2007. The only time a cone meters calibration changes is when there is a physical change to the meter, such as wear, contamination, cone deflection etc. However, it is recognized here that often it is difficult for the operator to be sure if there has been a slight change in geometry. As with all flow meters, one confirmed way to guarantee a previous calibration is still valid is to recalibrate.

5. <u>The Cone Meters High Resistance to Disturbed Inlet Flow</u>

The cone meter is renowned for being extremely resistant to disturbed inlet flow. Most flow meters are very sensitive to flow disturbances and require a fully developed symmetric flow profile at the meter inlet. This is achieved by setting the meters location at various distances

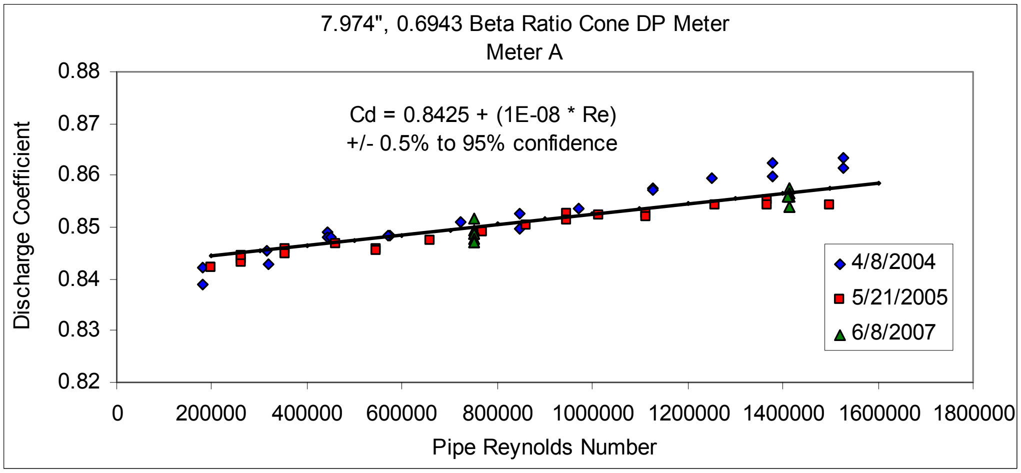

Figure 8. The repeat calibration results of one cone meter.

downstream from various obstructions and / or including a flow conditioner. The cone meter is not completely immune to upstream flow disturbances but it has been proven to be considerably less sensitive to most flow disturbances than other meters. Hence, the cone meter can be used in applications where long straight pipe work is not available and other meters can not be applied.

There are a few papers that suggest that the cone meters sensitivity is higher than claimed by the cone meter manufacturers. However, the reality is these papers are generally scientifically flawed. The “comparison tests” between the meters on relative sensitivities to upstream flow disturbances do not compare like for like. Typically an extremely small cone size, i.e. an excessively high beta ratio like 0.85, is chosen to be compared to another DP meter design of a more common mid-size beta ratio, like 0.6. The cone meters resistance to upstream flow disturbances reduces at a beta above 0.8. However, the common beta range of a cone meter is 0.45 to 0.75 (although 0.8 beta ratio cone meters are in use).

The truth regarding cone meter insensitivity to flow disturbances can be found in the API 22.2 test reports. This API test protocol allows a neutral test laboratory to test any DP meters sensitivity to upstream disturbances. The cone meter has been tested by a neutral laboratory according to API 22.2 and the results released by a cone meter manufacturing company (see Peters [3[). Other neutral tests have also confirmed the generic cone meters remarkably low sensitivity to upstream flow disturbances. Figures 9 thru 16 show testing done at CEESI in 2009 (see Steven [4]) to find the flow disturbance sensitivity of a 4”, 0.63 beta ratio cone meter. Figure 9 shows the baseline. Figure 10 shows a Double Out of Plane Bend (DOPB) at 0D upstream of the meter. Figure 11

Fig 9. Baseline Installation

Fig 10. DOPB, 0D up

Fig 11. DOPB 0D up & HMOP 2D down

Fig 12. DOPB 0D up & TOPB down

Fig 13. HMOP 6.7D up

Fig 14. HMOP 8.7D up

Fig 15. HMOP 2D down

Fig 16. 3” Swirl Generator + Expansion 9D up

shows a DOPB at 0D upstream of the meter and a Half Moon Orifice Plate (HMOP) at 2D downstream of the meter. (Note that a HMOP models the effect of a half open gate valve.) Figure 12 shows a DOPB at 0D upstream of the meter and a triple out of bend at 0D downstream of the meter. Figures 13 & 14 show a HMOP at 6.7D & 8.7D upstream of the meter respectively. Figure 15 shows a HMOP 2D downstream of the meter. Figure 16 shows a swirl generator generating extreme swirl before a 3” to 4” expansion at 9D upstream of the meter. Some of these flow disturbance tests are the most extreme ever tested on a cone meter. The results are shown in Figure 17. Note that the baseline calibration shows a discharge coefficient fitted across the Reynolds Number range to ±0.5%. The cone meters resistance to the extreme flow disturbances is clearly seen. Of the nine different disturbances, and note more are listed than pictures shown,

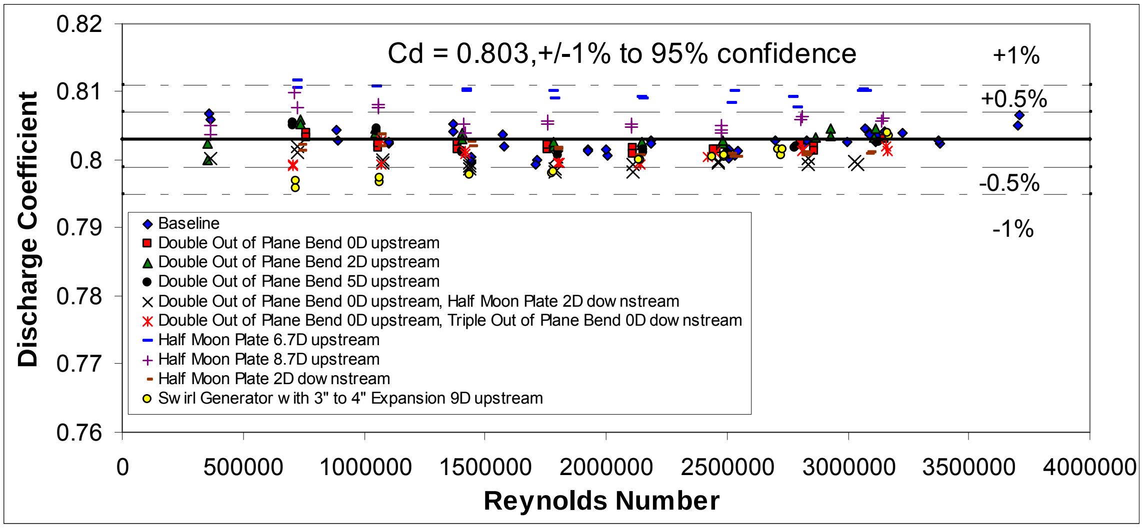

Figure 17. Complete Results of Cone Meter Performance with Flow Disturbances.

six of them did not shift the baseline calibration results more than the uncertainty of the baseline, i.e. the meters performance was still ±0.5%. Of the other three, which are some of the most extreme conditions a meter could encounter, the effect on the cones meters discharge coefficient, i.e. the bias induced, is barely 0.5% beyond the standard uncertainty. That is, all test results for all the extreme flow disturbances never varied from the baseline calibration discharge coefficient by more than ±1%. This cone meter result shows the cone meter to be extremely insensitive to flow disturbances issues. The other common DP meters on the market are far more sensitive to flow disturbances. Therefore, if a cone meter is properly calibrated across the full Reynolds number of the application and the resulting discharge coefficient known to ±0.5%, it is reasonable to expect that even with installations with extreme flow disturbances the meters actual flow rate uncertainty increases by no more than an additional 1% beyond this baseline value. This can not be said of other DP meters. Of course like all DP meters the bias due to the flow disturbance can be removed by calibrating the meter in the pipe configuration for which it is to be used.

6. Diagnostic Methods for Cone Meters

A proprietary cone meter diagnostics system exits that can be incorporated into the standard system. Figure 18 shows a sketch of a cone meter with the required instrumentation. A graph depicting the (simplified) pressure fluctuation through the meter is also presented. There is an extra pressure tap downstream of the cone. In addition to the standard inlet pressure and traditional DP, ΔP_t (see Figure 2) this enlarged system also reads the permanent pressure loss, ΔP_{PPL} (i.e. the pressure difference between upstream and downstream pressure tap) and the recovered DP, ΔP_r (i.e. the pressure difference between the downstream and cone pressure taps). The sum of the permanent pressure loss and the recovered DP equals the traditional DP. Hence, in order to find all three DP's only two must be read, with the third being inferred. Just as in section 2, where an expression was created linking the traditional DP to the mass flow rate the

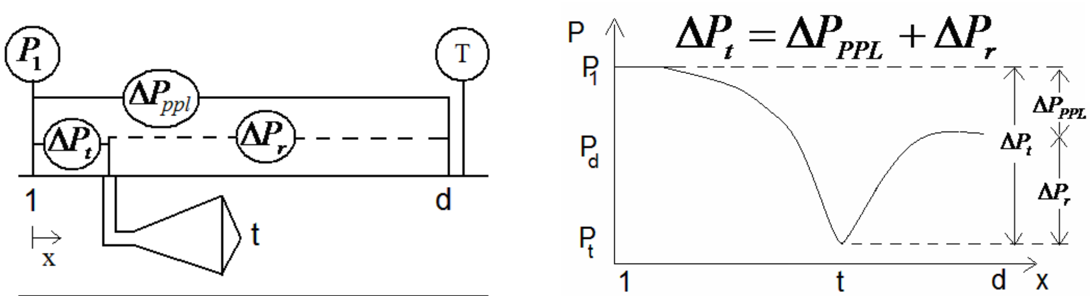

Figure 18. Cone Meter Sketch with Instrumentation and Pressure Fluctuation Graph.

same can be done for these other DP's (see Steven [4]). The resulting three flow rate equations are equations 9, 13 & 14:

Traditional Flow Equation: $\dot{m}_t = EA_tYC_d\sqrt{2\rho\Delta P_t}$, uncertainty ± x% --- (9)

Expansion Flow Equation: $\dot{m}_r = EA_tK_r\sqrt{2\rho\Delta P_r}$, uncertainty ± y% --- (13)

PPL Flow Equation: $\dot{m}_{PPL} = AK_{PPL}\sqrt{2\rho\Delta P_{PPL}}$, uncertainty ±z% --- (14)

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. A represents the meters inlet cross sectional area. 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. Therefore, the extra downstream pressure tap turns the single meter body into three flow meters. As all three flow equations are predicting the same flow rate there is potential to compare the three flow rate predictions and hence this is a diagnostics system. The respective flow rate prediction uncertainties (found by calibration) are denoted by x%, y% & z%. A correctly operating meter will have no pair of flow predictions differing by more than the sum of the two uncertainties. The three flow rate comparison percentage differences are:

Traditional to PPL Meter Comparison: $\psi\ \% = \left\{\left(\dot{m}_{PPL} - \dot{m}_t\right)\Big/\dot{m}_t\right\} * 100\%$ -- (15a)

Traditional to Expansion Meter Comparison: $\lambda\ \% = \left\{\left(\dot{m}_r - \dot{m}_t\right)\Big/\dot{m}_t\right\} * 100\%$ -- (15b)

PPL to Expansion Meter Comparison: $\mu\ \% = \left\{\left(\dot{m}_r - \dot{m}_{PPL}\right)\Big/\dot{m}_{PPL}\right\} * 100\%$ -- (15c)

This diagnostic methodology uses the three individual DP's to independently predict the flow rate and then compares these results. However, it is possible to take a different approach. The Pressure Loss Ratio (or "PLR") is the ratio of the permanent pressure loss to the traditional DP. The PLR is constant for cone meters operating with single phase homogenous flow. Therefore, the cone meter has a constant PLR for a set geometry. Note that equation 16 is a rule for all cone meters:

$$\frac{\Delta P_r}{\Delta P_t} + \frac{\Delta P_{PPL}}{\Delta P_t} = 1 \quad \text{--- (16)} \quad \text{where} \quad \frac{\Delta P_{PPL}}{\Delta P_t} \text{ is the PLR.}$$

As we know the PLR is a set value for a given geometry DP meter then equation 16 is also showing that the ratio of the recovered to the traditional DP's must then also be constant. In turn this means that the ratio of the recovered to PPL DP's must then also be constant. That is, all DP ratios available from reading the three DP's are constant values for any given cone meter and can be found with their uncertainties by the same calibration that finds the three flow coefficients. Here is another diagnostic method. From calibration 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%

so the read DP ratios can be compared to the calibrated values. Let α % denote the difference between the read to calibrated PLR. Let γ % denote the difference between the read to calibrated PRR. Let η % denote the difference between the read to calibrated RPR.

$$\alpha\ \% = \{[PLR_{actual} - PLR_{calibration}]/ PLR_{calibration}\}*100\% \quad \text{--- (16a)}$$

$$\gamma\ \% = \{[PRR_{actual} - PRR_{calibration}]/ PRR_{calibration}\}*100\% \quad \text{--- (16b)}$$

$$\eta\ \% = \{[RPR_{actual} - RPR_{calibration}]/ RPR_{calibration}\}*100\% \quad \text{--- (16c)}$$

The calibration of a cone meter can produce six meter parameters with six uncertainties. The parameters with uncertainties are the discharge coefficient, expansion flow coefficient, PPL coefficient, PLR, PRR & RPR. ***These twelve calibration values give a comprehensive profile the cone meter.*** Together they show the complete characteristics of that 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 possible situations that should signal an alarm.

No Alarm	ALARM	No Alarm	ALARM
$\psi\%/(x\%+z\%)<1$	$\psi\%/(x\%+z\%)>1$	$\alpha\%/a\%<1$	$\alpha\%/a\%>1$
$\lambda\%/(x\%+y\%)<1$	$\lambda\%/(x\%+y\%)>1$	$\gamma\%/b\%<1$	$\gamma\%/b\%>1$
$\mu\%/(y\%+z\%)<1$	$\mu\%/(y\%+z\%)>1$	$\eta\%/c\%<1$	$\eta\%/c\%>1$

Table 1. The cone meter possible diagnostic results.

For practical use, this diagnostic information must be easily accessible and understandable at a glance by any technician level meter operator. A graphical representation of the meters health updated real time (and also archived for later analysis if required) is simple and effective. Figure 19 shows a cone meter diagnostic plot. On the graph a box with co-ordinates of unity has been superimposed. Each DP pair has a flow rate prediction comparison related to the allowable difference (x-axis) and a DP ratio compared to the calibration value related to the allowable difference (y-axis). If all points are inside the box the diagnostics system does not see any meter problem. If any one point or more is outside the box then the meter is no longer operating as expected. This triggers a malfunction warning.

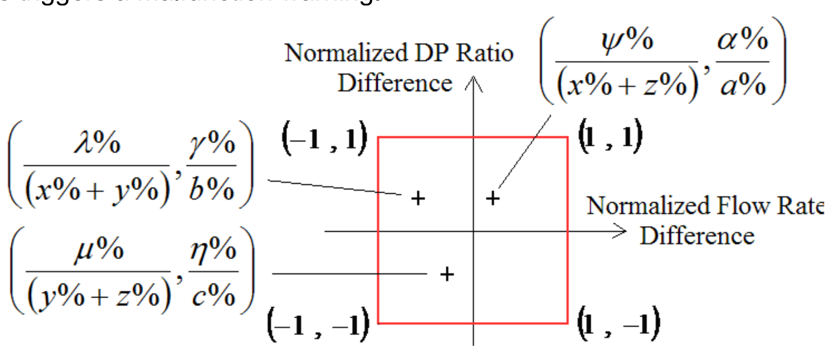

Figure 19. A diagnostic calibration box result.

Finally, let us look at a diagnostic example. Figure 20 shows two diagnostic results. The black hollow points are for the meter in correct operation installed with a DOPB at 0D upstream & HMOP 2D downstream (see Figure 11). The calibration data used was from the standard calibration with the long straight pipe length (as shown in Figure 9). Note that the points are all in the box correctly showing that the meter was operating correctly. This indicates that not just the discharge coefficient but also all the other diagnostic parameters are relatively insensitive to the inlet flow disturbance. (This is discussed in detail by Steven [4]). Figure 21 shows a nut trapped at the cone. Figure 20 also shows the diagnostic result when the cone was installed with a DOPB at 0D upstream & a HMOP 2D downstream (again see Figure 10) and with the nut trapped at the cone. The resulting flow rate bias induced by the nut was +5%. Figure 20 shows that the diagnostics show the operator a problem exists. This is a random example. The cone meter

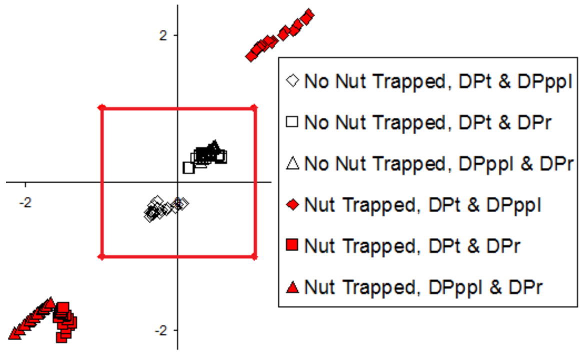

Figure 20. Correct & incorrect meter operation.

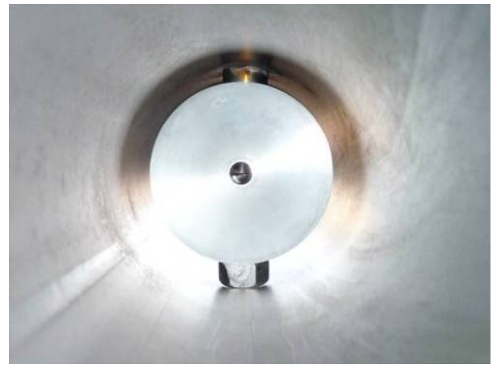

Figure 21. Trapped nut looking upstream

diagnostics have been shown to be sensitive to many common cone meter problems, such as incorrect geometry keypad entry of the inlet diameter or cone diameter, incorrect keypad entry of parameters such as the discharge coefficient, a damaged cone, a partial blockage at the cone, wet gas flow etc.

7. Conclusions

Cone meters are generic DP meters. They operate according to the same physical principles as the other DP meters. Cone meters have pros and cons when being compared to other DP meters.

Like many other meters, cone meters must be calibrated across the applications full Reynolds number range. The operator should be aware that a manufacturer's water flow calibration range often doesn't cover a gas flow applications full Reynolds number range. The operator should also be aware that cone meters built to a nominally identical design can have small but significant geometric differences due to manufacturing tolerances. Hence, each cone meter must be individually calibrated and the resulting calibration data is unique to that meter only and can not be transferred to another nominally similar meter. However, when properly calibrated a cone meter can have up to a ±0.5% uncertainty across a 10:1 turndown.

A calibrated cone meter is very **insensitive** to flow disturbance issues. The meter continues to correctly measure the fluid flow rate even with extreme flow disturbances that would make many other designs have significant flow rate prediction errors. Finally, it should be noted that the cone meter now has comprehensive diagnostics available if required thereby giving assurance to the operator that the meter is functioning correctly.

8. References

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