Cone DP Meter Calibration Issues

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1. Introduction

Cone DP flow meters are becoming increasingly popular in the oil and gas industry. A cone DP meter is a member of the generic Differential Pressure (DP) meter family and operates according to the same physical principles as other DP meter types.

ISO 5167 [1] states the performance of orifice plate, nozzle, Venturi nozzle and Venturi DP meters across set geometry designs, over particular ranges of flow conditions. ISO 5167 covers these meters as they have a long history of research where the massed data sets are publicly available for scrutiny. However, ISO 5167 does not cover cone DP meters as the patent protection has only recently lapsed and no independent research has yet shown that cone DP meters of set geometries have repeatable and reproducible performances over given flow condition ranges.

This paper reviews cone DP meter data from CEESI independent research, a CEESI wet gas Joint Industry Project and multiple third party[1] tests. The cone DP meters discussed are produced by multiple manufacturers. Performance comparisons are made between nominally identical cone DP meters. The relative merits of calibrating cone DP meters with low Reynolds number water flows or high Reynolds numbers gas flows will be discussed. The pros and cons of cone DP meter periodic re-calibration is also discussed. The effect of damage changing the cone alignment will be considered. Finally, the prospect of cone DP meters being eligible for inclusion in ISO 5167 is discussed.

2. The Cone DP Meter Geometry and Principles of Operation

Figures 1 shows a schematic sketch of a cone DP meter. There is an inlet (denoted with suffix "1") of known area (A_1) where the inlet pressure (P_1) is read. Inlet pressure is usually read with one pressure port at the same radial position as the cones support bar but this can change between meters. A cone DP meter primary element consists of a support bar (which can be a variety of sizes relative to the cone) downstream of the high pressure port, holding a cone. The cones apex is attached to this support bar and pointing into the flow (at a half angle, $\theta = 26^0$). A second cone of shorter length extends from the base of the first upstream cone, hence with the apex pointing downstream (at a half angle of 67.5^0, i.e. a base to cone angle, $\psi = 22.5^0$). The low pressure port[2] (denoted with suffix "t") extends through the cones and up through the support bar. The centre line of the cones should be aligned with the centre line of the pipe / meter body. The minimum cross sectional flow area (or "throat") of a cone DP meter (A_t) is therefore the annular ring between the circumference of the communal base of the cones (or "beta edge") and the

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[1] All third party data has been blinded to protect the privacy of individual cone DP meter owners.

[2] The most common design of cone DP meter reads the low pressure at the back face of the cone, i.e. in the cones wake. However, a minority of cone DP meters have the low pressure port on the meter wall, in the vicinity of directly downstream of the cone. This paper only discusses the common design.

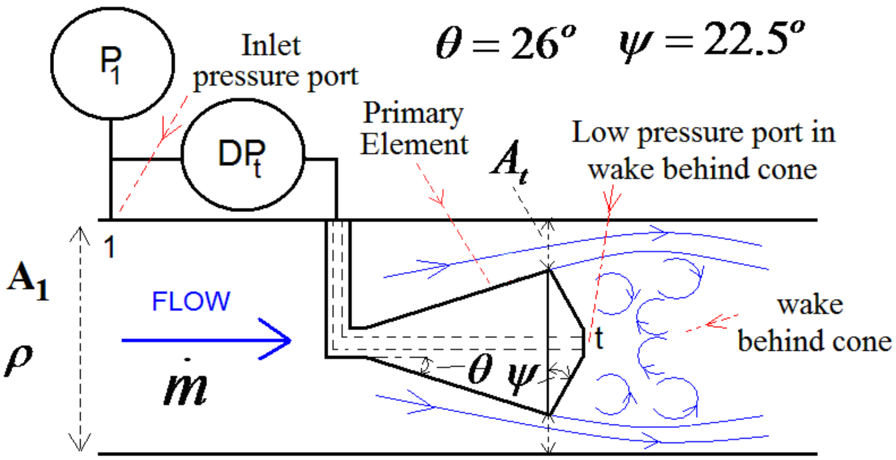

Fig 1. Sketch of a standard cone DP meter with flow profile, pressure and DP transmitters

meter body wall. The distance between the centre lines of the upstream pressure port and the cone support is usually 2⅛" in order to facilitate close coupling with a DP transmitter. However, this distance can be changed as required for specific applications.

When metering a mass flow rate ($\dot{m}$) or volume flow rate ($\dot{Q}$) with a cone DP meter, the high pressure is read from the inlet pressure port (P_1) and the differential pressure (or "DP") is read as the difference between the inlet pressure and the low pressure (P_t) at the centre of the back of the cone. (i.e. $\Delta P = P_1 - P_t$). That is, the low pressure is the pressure in the cones "wake". A wake is a highly turbulent area of flow, deficient in momentum, directly behind bodies immersed in a fluid flow.

The cone (i.e. the generic) DP meter mass and volume flow rate equations are shown here as equations 1 & 2 respectively.

$$\boxed{\dot{m} = EA_t\varepsilon C_d\sqrt{2\rho\Delta P}} \text{ --- (1)} \qquad \boxed{\dot{Q} = EA_t\varepsilon C_d\sqrt{\frac{2\Delta P}{\rho}}} \text{ --- (2)}$$

Note that ρ represents the fluid density. E is the "velocity of approach" and A_t is the "throat area". These are both constants for a set DP meter geometry. The velocity of approach is solely a function of the beta ratio as shown in equation 3. The cone DP meter beta ratio is calculated by equation 4 (where D is the meter inlet diameter and d_c is the base cone diameter). The throat area A_t is calculated by equation 5.

$$E = \frac{1}{\sqrt{1-\beta^4}} \text{ -- (3),} \quad \beta = \sqrt{\frac{A_t}{A_1}} = \sqrt{1-\left(\frac{d_c}{D}\right)^2} \text{ -- (4),} \quad A_t = \frac{\pi}{4}\left(D^2 - d_c^2\right) \text{ -- (5)}$$

The expansibility (ε) accounts for gas density fluctuation through the meter. In the US this parameter is called the expansion factor and denoted by the letter "Y". The cone DP meter expansibility was developed by Stewart et al [2] and is shown as equation 6. Note that κ is the fluids isentropic exponent. For liquids expansibility is unity.

$$\varepsilon = 1 - \left\{ \left(0.649 + \left(0.696 \beta^4 \right) \right) * \left(\frac{\Delta P}{\kappa P_1} \right) \right\} \text{ --- (6)}$$

The final component to the mass and volume flow rate equations is the discharge coefficient, C_d. The discharge coefficient of cone (and all generic) DP meters is defined by equation 7. The numerator of equation 7 is the actual mass flow rate. The denominator is the DP meter theoretical flow rate calculation where no real world effects are accounted for. Therefore, the discharge coefficient of cone (and all generic) DP meters is defined as the ratio of the actual to the theoretically calculated mass flow rates.

$$C_d = \frac{\dot{m}_{actual}}{\dot{m}_{theoretical}} = \frac{\dot{m}_{actual}}{E A_t \varepsilon \sqrt{2 \rho \Delta P_t}} \text{ --- (7)}$$

The discharge coefficient corrects the theoretical flow rate prediction for all inaccurate assumptions made by the theoretical equation development. That is, the discharge coefficient accounts for all unpredictable factors. Calibration of cone (and all generic) DP meters means testing the meter to find the discharge coefficient. As the actual flow rate through any flow meter is never truly known, it is standard practice to use a calibration facilities low uncertainty reference flow meter output as the "actual" flow rate. A consequence of this is that a cone flow meter uncertainty rating can therefore never be less than the reference meter uncertainty rating.

A simple calibration method is to take an average or mid point discharge coefficient across the calibration Reynolds number (Re) range. However, it is sometimes necessary to data fit the discharge coefficient to the Reynolds number to get a lower flow rate uncertainty. The Reynolds number is shown in equation 8, and the data fit to the discharge coefficient in equation 9.

$$\mathrm{Re} = \frac{inertia\ \ forces}{viscous\ \ forces} = \frac{\rho \bar{U} D}{\mu} = \frac{4 \dot{m}}{\pi \mu D} = \frac{4 \rho \dot{Q}}{\pi \mu D} \text{ --- (8)}, \qquad C_d = f_1(\mathrm{Re}) \text{ --- (9)}$$

Note that $\bar{U}$ is the average velocity, μ is the fluid viscosity and f_1 is a *unique* data fit per DP meter, of discharge coefficient to Reynolds number. If a data fit is used rather than a constant discharge coefficient the mass or volume flows are calculated by substituting equation 8 into equation 9, and equation 9 into equations 1 or 2 respectively and iterating.

Note, that the cone DP meter does not have a special, unique or different flow rate equation that fundamentally differs from any other DP meter flow equation. The basic theory of operation is the same as with all DP meters. However, it should be noted that compared to other DP meters the cone DP meter does have some practical advantages, e.g. a significantly higher resistance to upstream disturbances (see Peters et al [3]).

3. Cone DP Meter vs. Venturi Meter Calibration Requirements

Two popular rival DP meter designs are the cone DP meter and the Venturi meter. The Venturi can sometimes be perceived to have an advantage as unlike the cone it is included in ISO 5167 [1]. Hence, for precise Venturi meter geometries, under a given range of flow conditions, no calibration is required to find the Venturi meters discharge coefficient. However, the cone DP meter must always be calibrated to find its discharge coefficient. Therefore, within the Venturi meter ISO scope the Venturi has an advantage, as not requiring calibration can significantly reduces the cost of the meter. However, it should be noted that ISO 5167 is <u>only</u> valid over a stated range of Venturi meter geometries and flow conditions. In fact, in many (if not most) natural gas production meter applications, the flow conditions are out with the limits of the ISO Venturi meter standard. Extrapolating the ISO discharge coefficient prediction to other conditions is not valid. In this situation the Venturi meter reverts to the status of all "non-standard[3]" DP meters (e.g. the cone DP meter) in as much as the discharge coefficient must be found by calibration at the range of flow conditions for which the meter will be used.

ISO 5167 includes a discussion on the high precision machined convergent section Venturi meter. This is the common type used to meter natural gas production flows. The limits of this meters ISO performance declaration are:

$$50 \text{ mm } (2") \leq D \leq 250 \text{ mm } (10")$$
$$0.4 \leq \beta \leq 0.75$$
$$2e5 \leq \text{Inlet Reynolds Number } (D) \leq 1e6$$

(Annex B of ISO 5167 gives an *informative discussion only* on the possible affects of higher Reynolds numbers with significantly increased discharge coefficient uncertainties suggested.) It is stated that under performance declaration the discharge coefficient is a constant, i.e. $C_d = 0.995$ to an uncertainty of ±1%. However, ISO 5167 also states:

"Research into the use of Venturi tubes in high-pressure gas [$\geq$ 1 MPa ($\geq$ 10 bar)] is being carried out at present. In many cases for Venturi tubes with machined convergent sections discharge coefficients which lie outside the range predicted by this part of ISO 5167 by 2% or more have been found. <u>For optimum accuracy Venturi tubes for use in gas should be calibrated over the required flowrate range</u>."

Furthermore, ISO also explain that a simultaneous use of the extreme values of D, β, Re(D) shall be avoided as otherwise the Venturi meter flow rate uncertainty is likely to increase. They therefore state that for <u>installations outside theses diameter, beta ratio, pressure and Reynolds number limits, it remains necessary to calibrate the meter in its actual conditions of service</u>.

Whereas Venturi meters are popular in the natural gas production industry most applications have pressures greater than 10 bar (abs) and Reynolds greater than 1e6 and many applications have pipe diameters greater than 10". *Therefore, in many (if not most) natural gas production applications the ISO Venturi meter standard is inapplicable.* Furthermore, Venturi meter performance outside the ISO limits has been researched. It is known that the ISO discharge coefficient is not always applicable and there can be reproducibility problems between nominally identical meters (e.g. Geach et al [4]).

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[3] "Non-standard" is defined here as any meter that does not have a standards body approved discharge coefficient prediction. This term is not to be associated with whether or not a meters manufacturing process is standardized.

Hence, the blind application of the ISO stated discharge coefficient could lead to flow measurement error. Therefore, Venturi meters with flow conditions outside the ISO scope should be calibrated across the full Reynolds number range of the meters application.

Cone DP meters must be calibrated across the full Reynolds number range of the meters application. Failure to calibrate the cone DP meter correctly can lead to high flow rate uncertainties. The scale of these cone DP meter uncertainties will be discussed in this paper. Therefore, both Venturi and cone DP meters should be individually calibrated, and hence, in most natural gas production applications the cone DP meter does not have a calibration cost disadvantage against a Venturi meter.

The cone DP meter is an increasingly popular meter, in part due to its high resistance to upstream disturbances. The cone DP meter is no longer patent protected. It is therefore a candidate for future inclusion in standards documents. However, an independent evaluation of cone DP meter repeatability and reproducibility is required as an initial step to discussing this meters possible future inclusion in standard documents. The authors now offer an evaluation of cone DP meter performance.

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% (and occasionally more). 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[4] is used to calibrate the meter. Therefore, a natural gas flow DP meter can be calibrated in an air flow calibration facility or a gas DP meter can be calibrated with a water flow calibration facility etc.. The single, but critical, stipulation is that the Reynolds number range of the application is met. 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 DP meter with a water flow can be attractive to both manufacturer and DP 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 8 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

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[4] In this statement, "fluid" means a Newtonian fluid. This statement is not true of non-Newtonian fluids.

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 DP 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 DP 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 DP 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 DP meters often have a discharge coefficient vs. Reynolds number relationship that is not constant this extrapolation can and does lead to substantial metering errors.

Cone DP meters operate according to generic DP meter rules. If these rules are met then the cone DP meter is likely to be a reliable flow meter capable of giving flow rates to an uncertainty of 0.5% across a 10:1 turndown[5]. As with all common DP meters there are no moving parts and therefore a properly calibrated and installed cone DP meter should be reliable and need little to no maintenance. If no damage, wear, trapped foreign objects or contamination issues occur then the calibration result, and hence the performance, should remain constant (as long as the instrumentation is properly maintained). However, failure to calibrate the cone DP meter correctly can lead to an increase in flow rate measurement uncertainty or a significant bias on the flow rate measurement. The following discussion shows examples of potential calibration issues with cone DP meters.

4a. The Necessity for Calibration Across the Applications Full Reynolds Number Range

If a DP 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. Examples are now given.

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[5] 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 1). 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.

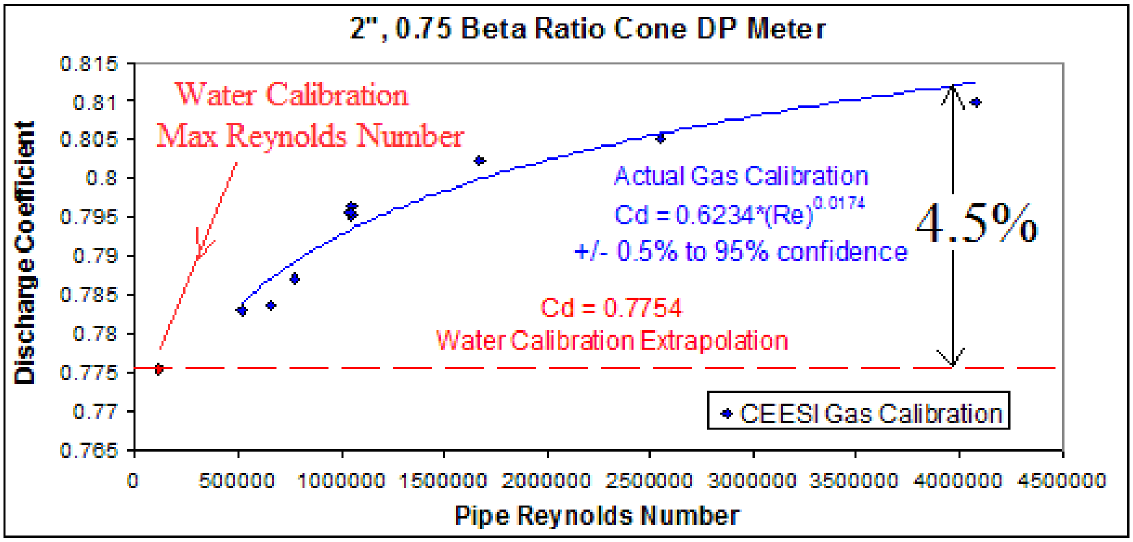

Fig 2. 2”, 0.75 beta ratio cone DP meter water and gas calibration results.

A 2”, 0.75 beta ratio cone DP meter was supplied to a gas flow application with a water calibration. The discharge coefficient was stated to be 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.

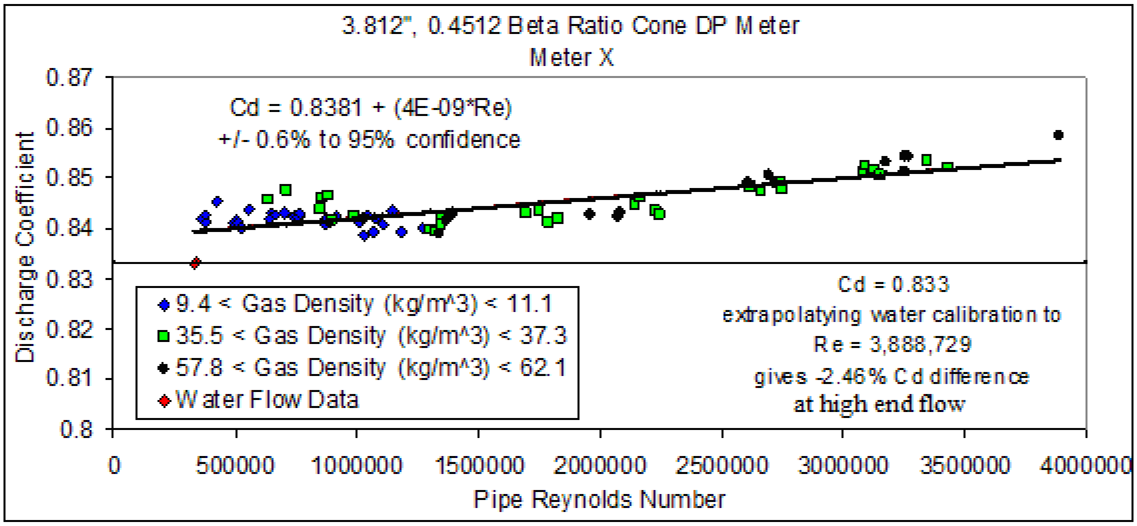

Fig 3. 4”, 0.45 beta ratio meter X, water flow calibrated and gas flow calibrated.

CEESI tested several cone DP meters as part of a wet gas flow research Joint Industry Project (JIP). The initial research was to confirm the meters gas flow performances as stated by the manufacturer. A cone DP meter manufacturer supplied a 4”, schedule 80, 0.45 beta ratio meter (say meter X) with a stated discharge coefficient set to 0.833 at 0.5% uncertainty. CEESI applied this manufacturer supplied discharge coefficient and discovered that the meter was consistently under predicting the gas flow rate. As the first meter was removed for inspection a second meter (say meter Y) of the same specification (built from the same drawing as meter X) was therefore dispatched to CEESI by the manufacturer. This had a manufacturer stated discharge coefficient of 0.807 and 0.5% uncertainty. It was subsequently discovered that both meters had been calibrated by the manufacturer with water flows only with a maximum Reynolds number of 340,000. The JIP had tested the meter at CEESI with gas flows at Reynolds numbers up to 4e6. All meter X data (i.e. the water and natural gas flow data) is shown plotted in Figure 3. As the Reynolds number increased beyond the limit of the water calibration it was seen that the discharge coefficient was not constant (as implied by the manufacturers supply of a constant value) but rather it increased with Reynolds number. Therefore, when the JIP extrapolated the water calibration found discharge coefficient to the highest Reynolds numbers tested the flow was under-predicted by 2.46%. Data fitting all the data, i.e. the water and the various pressure[6] gas flow data sets gave a flow rate uncertainty of ±0.6%[7] for the 10:1 turndown. (It is very likely that the meter would have calibrated to ±0.5% if a gas calibration facility had been used.)

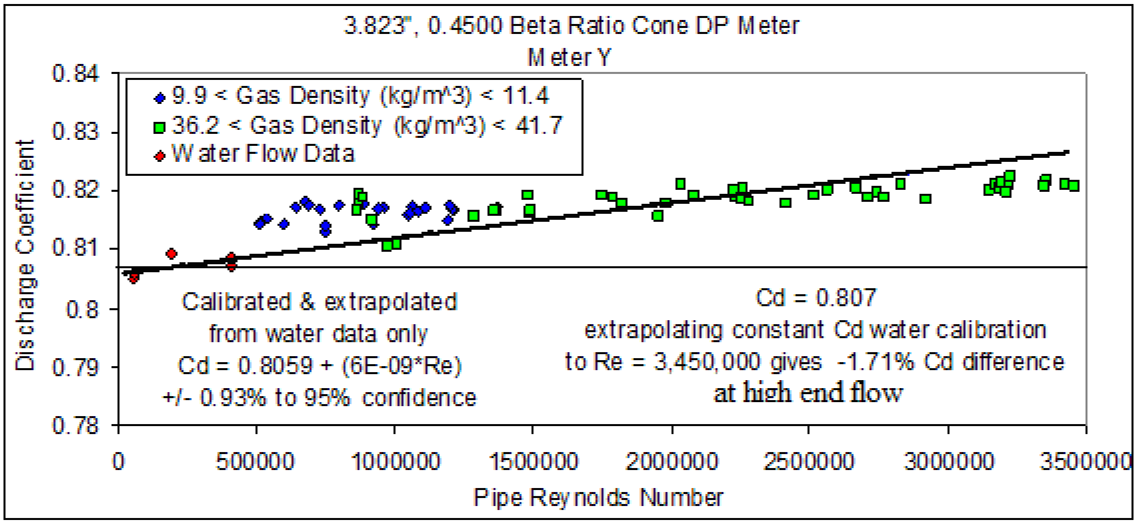

Fig 4. 4", 0.45 beta ratio meter Y, water flow calibrated only.

The replacement cone DP meter (Meter Y) was produced to the same specification as the original meter (Meter X). However, this time the manufacturer had calibrated Meter Y across a range of Reynolds numbers within their water calibration facilities range and not simply the highest Reynolds number obtainable. However, this data could be interpreted as the discharge coefficient having a constant value or having a relationship with Reynolds number. Figure 4 shows the manufacturer water flow data and the CEESI gas flow data. The results on the whole combined data set of taking a constant discharge

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[6] Note that varying the pressure / gas density made no difference to the calibration. As long as the Reynolds number value is met any DP meter is calibrated correctly regardless of the line pressure.

[7] Note that the CEESI wet gas loop is not designed as a gas flow calibration system and therefore does not give the same standard of gas reference metering as a meter calibration system. For example, one CEESI gas flow meter calibration system has a reference (critical flow Venturi) meter with an uncertainty < ±0.35%. The CEESI wet gas test facility running dry has a reference (turbine) meter with an uncertainty < ±0.7%. All uncertainties discussed in this paper refer to the difference between test and reference meters.

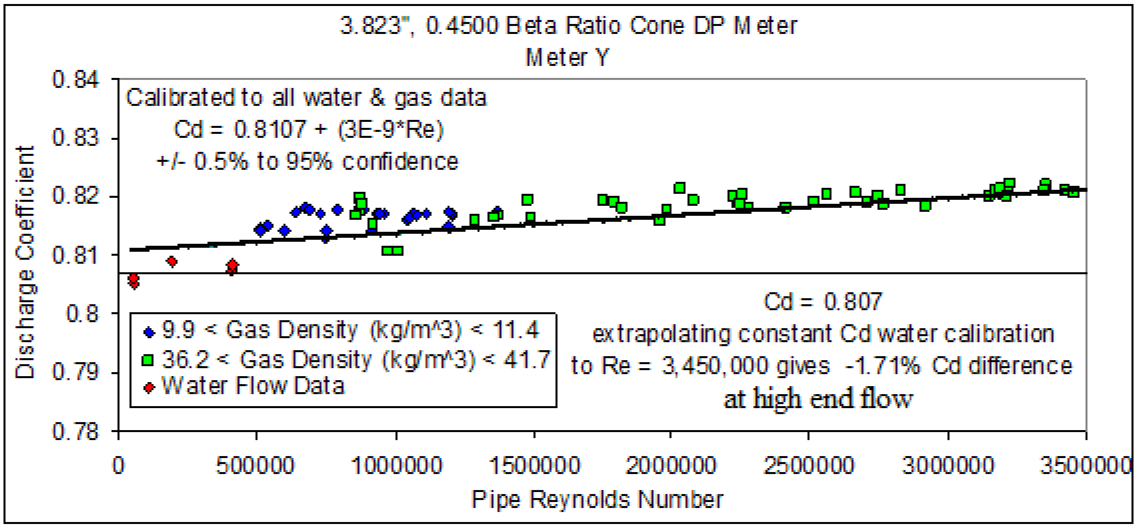

Fig 5. 4", 0.45 beta ratio meter Y, calibrated with all data.

coefficient from the water data and fitting a linear line through the water data is shown. The water flow data based constant discharge coefficient again under-read the gas flow rate at the upper end of the applications Reynolds number by up to -1.71%. The linear line fitted to the water data only (which simulates only having the water data available for meter calibration) improved the situation. This linear fit fitted all the data to an uncertainty of ±0.93% across a 10:1 turndown. However, Figure 5 shows that by data fitting all the water and gas flow data (i.e. by calibrating the meter correctly) the resulting uncertainty was ±0.5%, across a 10:1 turndown. That is, when calibrated correctly, the meter met the manufacturer's uncertainty claim.

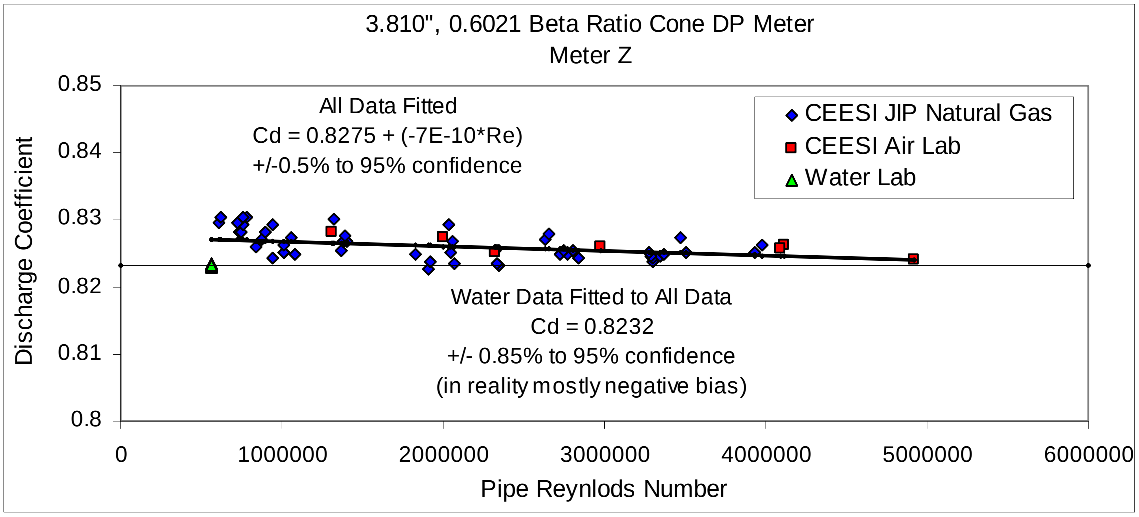

Fig 6. 4", Schedule 80, 0.60 Beta Ratio Meter, Water and Gas Flow Calibrated.

Figure 6 shows the calibration results of a 4", 0.6 beta ratio cone DP meter (Meter Z). The water calibration point is the maximum Reynolds number achieved at a water flow facility. The resulting discharge coefficient (C_d=0.8232) was supplied. The natural gas flow test data at various pressures is shown (as one data group) along with a later air calibration at CEESI. Fitting all three data sets allowed a linear fit to predict the discharge coefficient to the manufacturers claimed uncertainty of ±0.5% across a 10:1 turndown. If the water based low Reynolds number calibration had been accepted and used by extrapolation, the resulting uncertainty would have been ±0.85%, across a 10:1 turndown. However, note from Figure 6, it could be argued that this is not really an increase in uncertainty but the introduction of a small bias as the water calibration data has a lower discharge coefficient than more than 95% of the higher Reynolds number gas flows. Note that Figures 2 thru 5 show a discharge coefficient to Reynolds number relationship with a positive gradient. This is not always the case as shown by Meter Z in Figure 6.

It is not good measurement practice to extrapolate cone DP meter (or any meter) calibrations to higher Reynolds numbers. Extrapolating low Reynolds number data sets to predict the discharge coefficient at high Reynolds numbers can give at best an increase in uncertainty, or a small bias, or worse, give gross errors. It is good practice to calibrate the meter across the full Reynolds number range of the application. Only then is a flow meter uncertainty statement meaningful. If a cone DP 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. The Necessity to Calibrate Each Individual Cone DP Meter

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 or two meters 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 DP 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 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.

The two 4”, schedule 80, 0.45 beta ratio meters discussed in section 4a where identical on paper. They were built by the same manufacturer, at the same fabrication shop, from the same drawing. 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

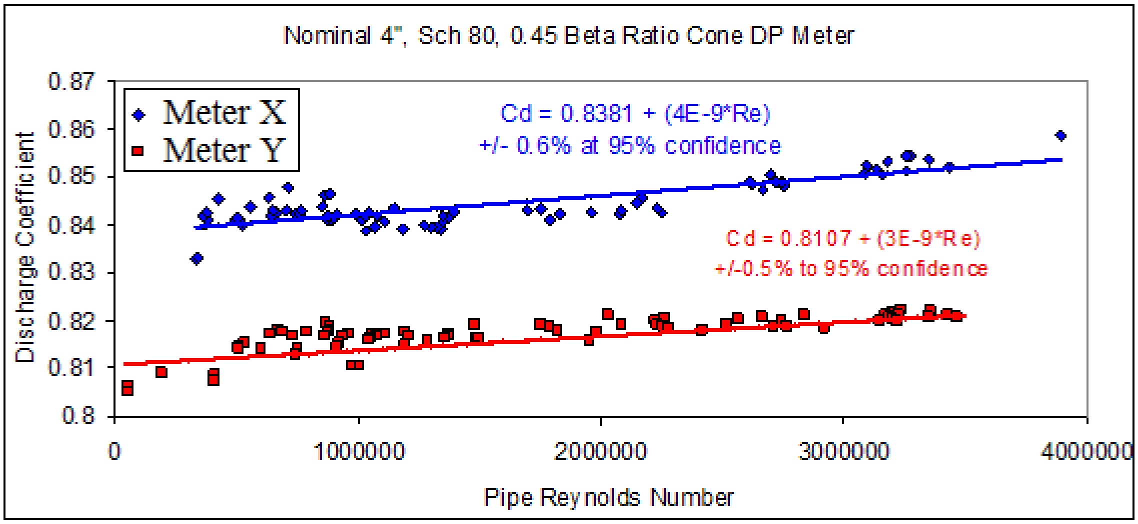

Fig 7. Comparison of two nominally identical cone DP meter calibrations.

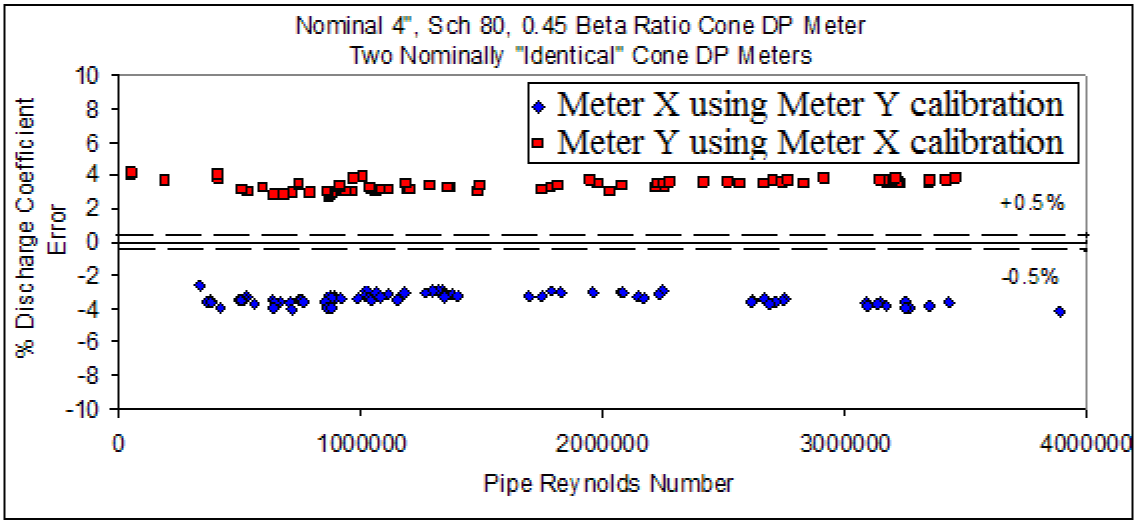

Fig 8. Applying data fits from one cone DP Meter to another of the same specification.

discharge coefficients. If one meter was calibrated only, and the result applied to the other meter (on the assumption it will behave the same), then the un-calibrated meter would have a significant bias in its flow rate predictions. Figure 8 shows this scenario. However, it is noteworthy that each meter individually calibrated across the Reynolds number range to give a low uncertainty across a relatively large turndown.

There is plenty of evidence that this is a typical result. Figure 9 shows the comparison of three 4", schedule 80, 0.75 beta ratio cone DP meters, two from one manufacturer and one from another. On paper they should have an identical performance. In reality all three meters have similar but not identical performances. Again, *individually* the meters calibrate to give an uncertainty of < ±0.6%[8] across relatively large turndowns. (Note that meter 2 required a non-linear fit to meet the ±0.5% uncertainty specification. Such fits,

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[8] Meter 1 only has data from a wet gas facility running dry. This facilities reference meter is not of gas meter calibration standard, hence causing higher uncertainty. It is therefore likely all three meters could be calibrated to ±0.5% uncertainty.

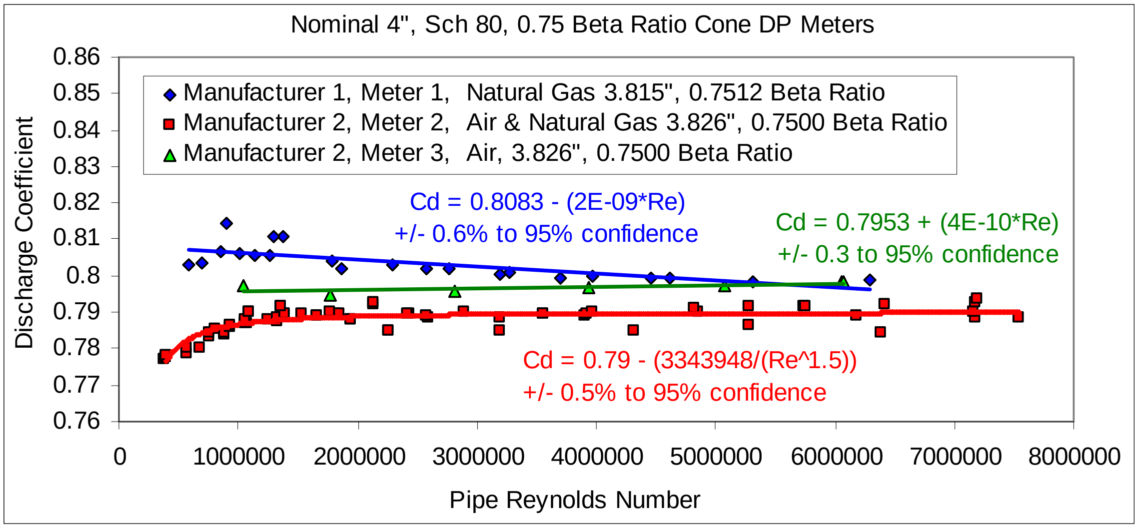

Fig 9. Comparison of nominally 4”, 0.75 beta ratio cone DP meter calibration data sets.

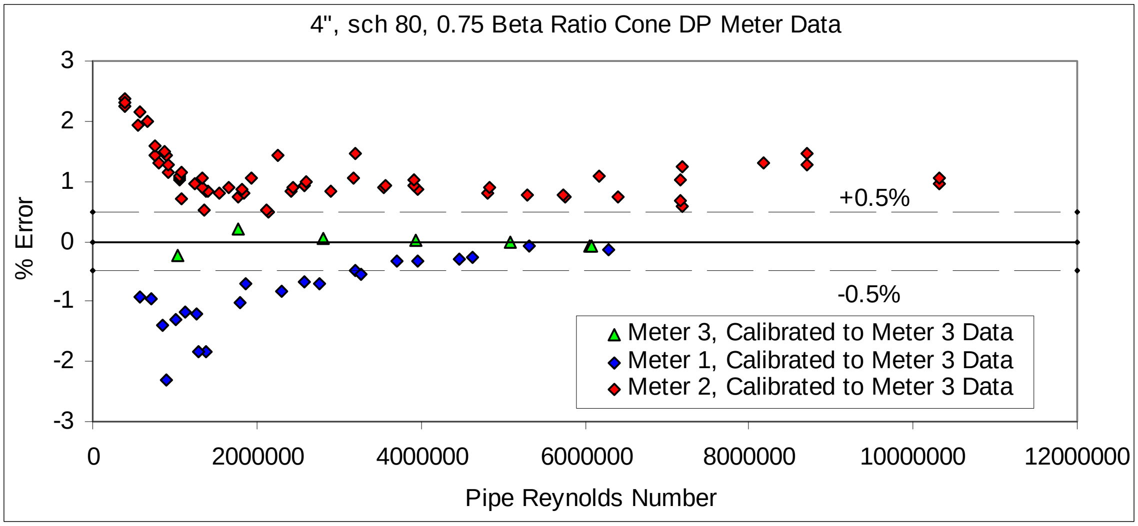

Fig 10. Results of applying one meter calibration to other same specification meters.

when required, are standard practice across industry.) If we assume that the meters have the same performance then we assume one calibration describes all three meter performances. Again, this assumption leads to significant flow metering errors. Figure 10 shows the induced metering error of applying meter 3’s calibration on meters 1 and 2. The resulting flow metering error can therefore be several percent. Note that these errors are a bias, not an increase in flow rate uncertainty. Finally, note that Figure 9 shows meter 2 with a distinct rise in discharge coefficient at the lower Reynolds number range before it levels off. If calibrated at low Reynolds number only and the result extrapolated to high Reynolds number a significant bias could exist.

A third example is shown in Figures 11 and 12. Four 8”, schedule 40, 0.7 beta ratio cone DP meters (say meters A, B, C & D) were built by one manufacturer and calibrated at CEESI across the full Reynolds number range of the application. Individually the meters were all found to have a ±0.5% performance across the full turndown. (The individual

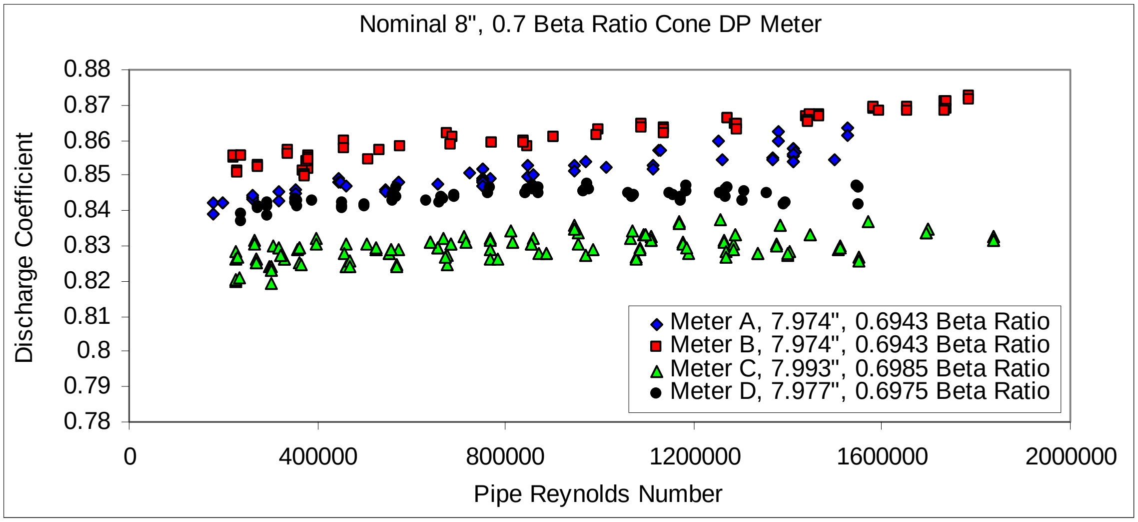

Fig 11. Four nominally 8", 0.70 beta ratio cone DP meter calibration data sets.

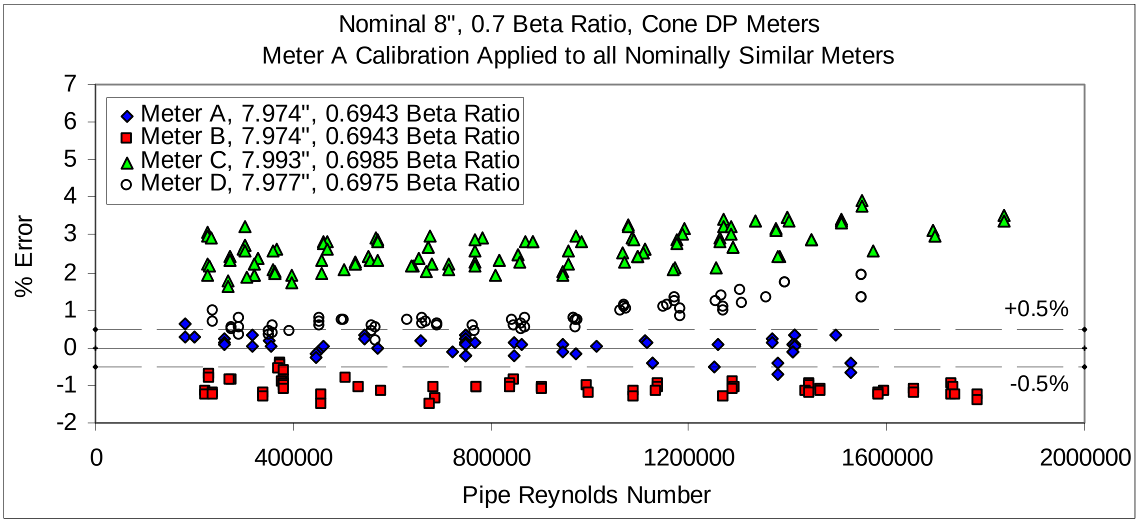

Fig 12. Results of applying meter A's calibration to meters of the same specification.

linear data fits are presented in section 4d.) The difference in performance of meters of the same specification is again clearly noticeable. Figure 11 shows that the variation in discharge coefficient value is approximately 5%. Figure 12 shows the result of accepting meter A as the calibration data for all four meters. This introduces significant biases for Meters B, C & D of up to 4%.

It is possible that two cone DP meters built from the same specification *could have* identical performances. Figure 13 shows two 14", schedule 40, 0.46 Beta Ratio cone DP meter calibrations. Here it was found that not only did the two meters (say meters E & F) both individually calibrate with a linear fit to a ±0.5% performance across the full turndown, but that they both had the same performance. Figure 14 shows the result of using each meters calibration on the other meter. In this case the meters uncertainty rating stayed at ±0.5%. It is therefore clear that multiple cone DP meters built to the same specification may or may not have the same performance. This situation will continue until such time as the cone DP meter manufacturers can guarantee that any small

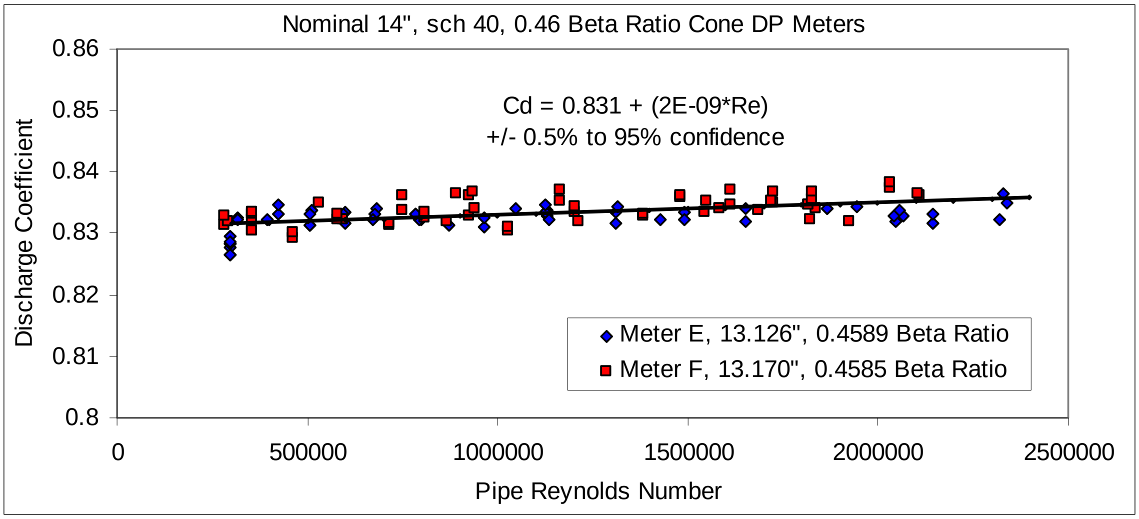

Fig 13. Calibrations of meter E & F, i.e. 14", 0.46 beta ratio cone DP meters.

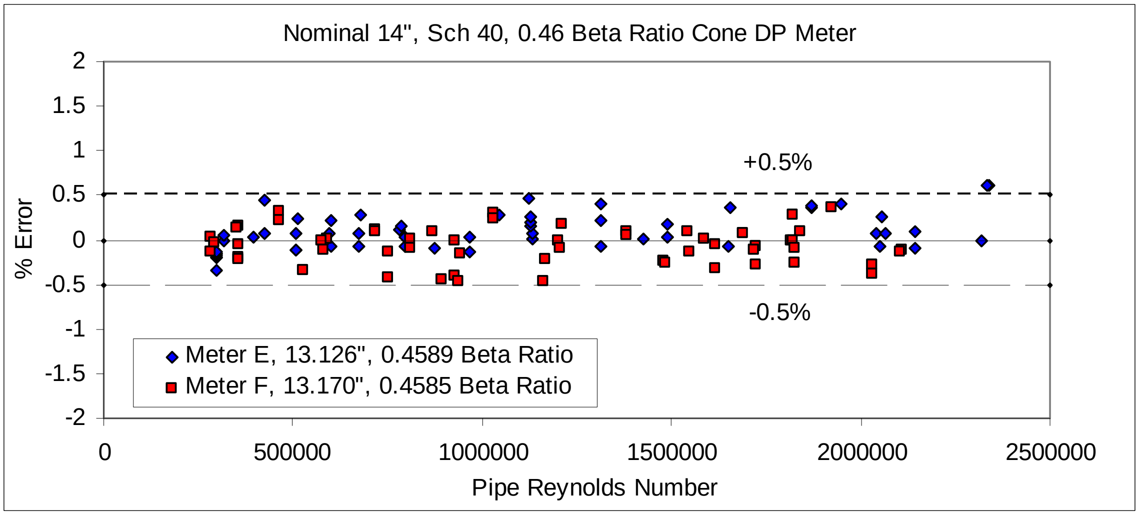

Fig 14. Applying meter E's calibration to meter B's performance and vice versa.

variations in meters built to one specification are small enough as to not affect the meters performance. However, as yet there is not enough information available to produce guidelines on the required manufacturing tolerances to ensure cone DP meters of the same specification have reproducible calibrations. Therefore, until such times as this information becomes publicly available with substantial third party data backing the reproducibility claims, each cone DP meter should be individually calibrated, across the full Reynolds number of the application, if a low flow measurement uncertainty is to be achieved. It therefore appears to be premature to be considering developing a cone DP meter standard.

4c. A Discussion on the Requirement for Periodic Re-Calibration

If a DP meter is of a set geometry then its performance (i.e. the relationship between the Reynolds number and the discharge coefficient) will be set. This is the basis for the ISO 5167 standards. It is the fact that cone DP meters often have differences in their manufacture that causes the discharge coefficient to shift between meters that are built from the same specification. If two cone DP meters were truly identical their performance would be identical and only one cone DP meter out of a batch of identical meters would require calibration for the performance of all the meters to be found. It therefore follows that if a particular cone DP meter is calibrated, then as long as the geometric shape of the meter has not changed (e.g. from contamination, erosion, corrosion, plastic deformation of the cone assembly due to adverse flow conditions, or no foreign object is trapped at the cone) then its calibration result will remain constant. That is, periodic re-calibration of any DP meter is only required if confirmation is required that the geometry has not changed. (However, note that all instrumentation must be regularly re-calibrated.)

Proof of this can be seen if we discuss meters A, B, C & D in section 4b. These data sets shown in Figures 11 are actually multiple data sets for each meter. These meters are recalibrated every year to assure the owner that the previous calibration is still valid. Each meters separate data sets are shown in Figures 15 through 18 respectively. Meters A, B & D had the same calibration result each year. Note that meter D has two calibration data sets on the same day. This is due to the procedure of the meter being calibrated as delivered to the facility and then cleaned of any contamination. As no significant difference is seen this indicates no significant contamination problem existed. Meter C has four data sets. One pair is a repeat set from 2004. This again is calibrations before and after cleaning. Here the meter was delivered as it left service, calibrated and then cleaned and re-calibrated. A small shift is seen indicating that the contamination level of this meter was enough to have caused a small shift in performance (see Figure 17, 2004 set 1). On cleaning, the meter returned to its standard performance (see Figure 17, 2004 set 2). The ±0.7% data fit in Figure 17 is for all the data, including the contaminated cone DP meter data set. If this data set is removed the meter can be shown to calibrate to ±0.5% like the other meters. This is a very common result. For example, meters E & F (in section 4b) also show repeat calibrations after periods of service. Figures 13 and 14 actually show multiple calibration data for each meter. No significant difference exists between periodic calibrations.

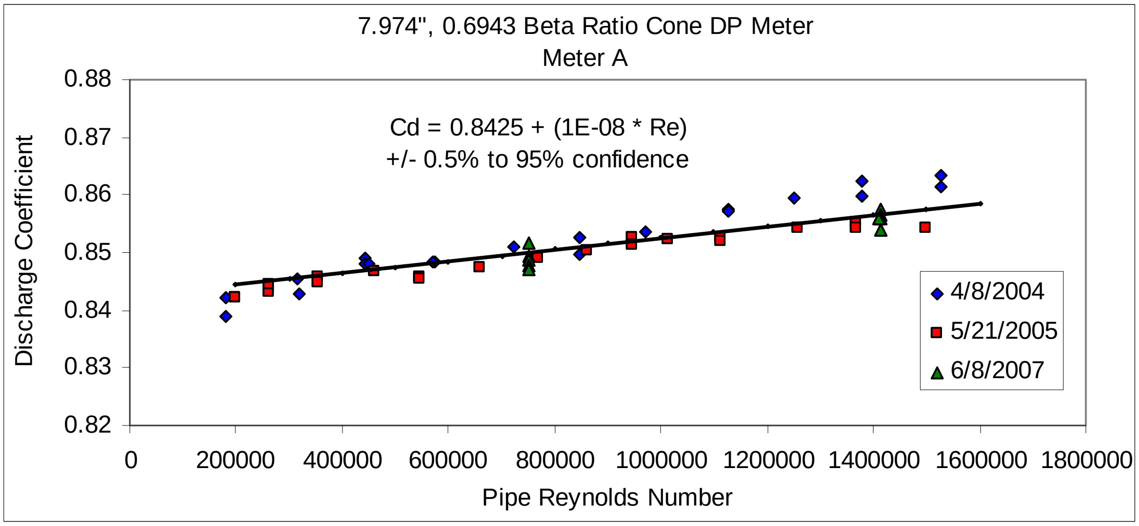

Fig 15. A comparison of repeat calibration results for meter A.

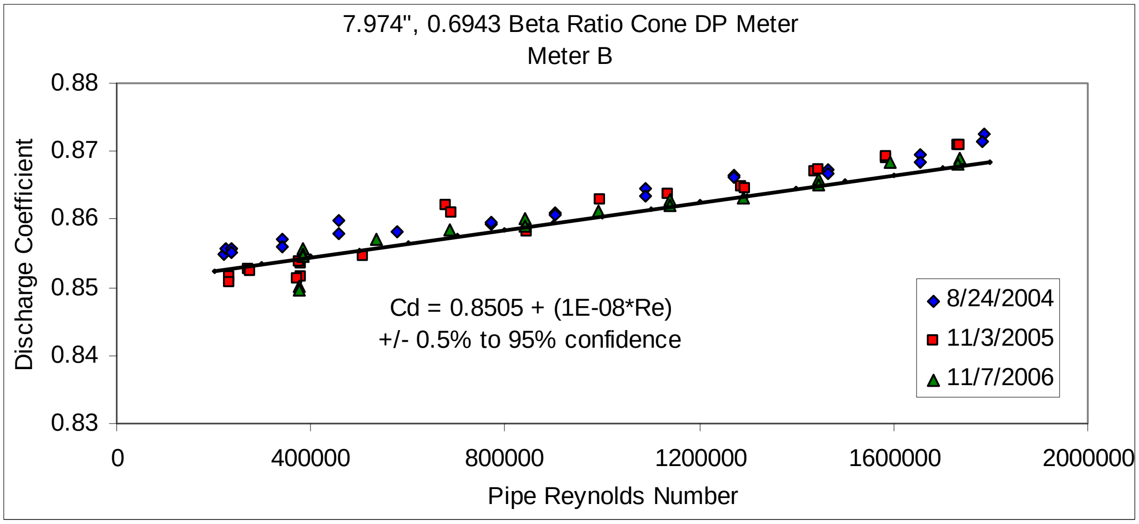

Fig 16. A comparison of repeat calibration results for meter B.

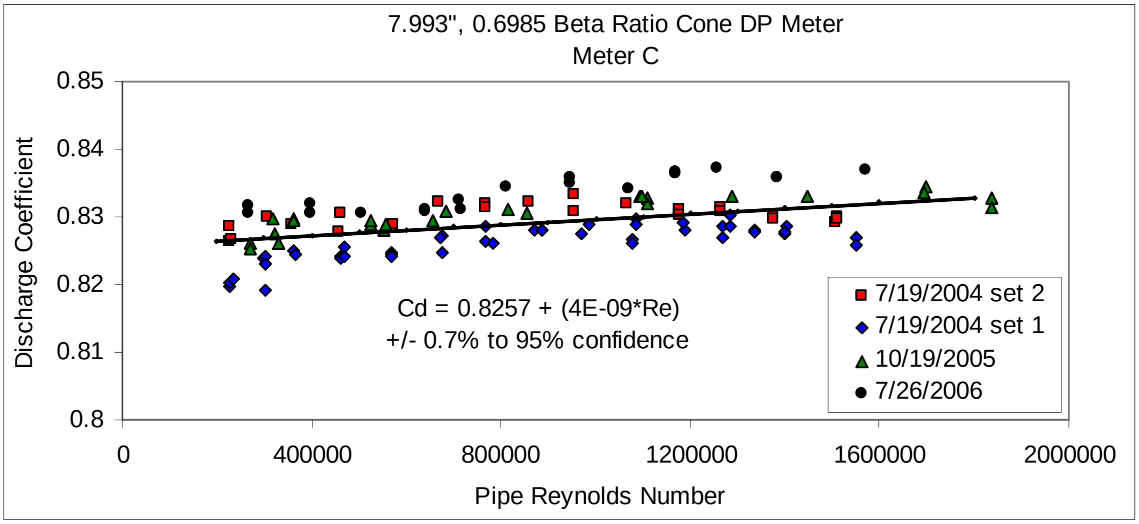

Fig 17. A comparison of repeat calibration results for meter C.

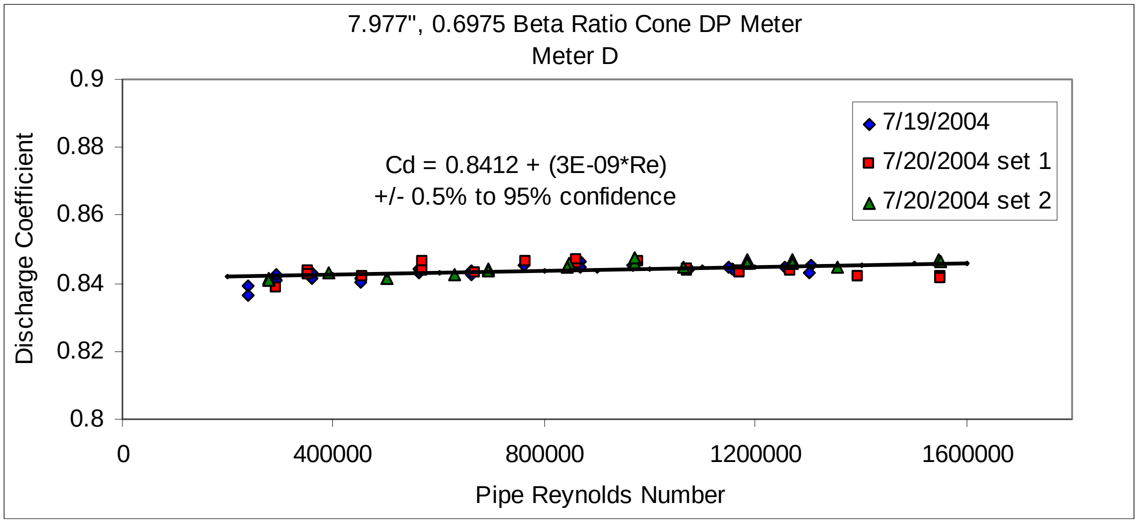

Fig 18. A comparison of repeat calibration results for meter D.

Hence, if no physical damage, contamination or throat blockage occurs to a cone DP meter, the calibration of the meters remains valid indefinitely. However, if physical damage, contamination or throat blockages are potential events in the meters application and the meter user requires a low flow measurement uncertainty, then periodic recalibrations of the meter can give the user assurance that the stated calibration flow measurement uncertainty is being achieved.

4d Issues with Estimating Discharge Coefficients with no Calibration

ISO 5167 [1] states that the Venturi meter has a constant discharge coefficient of 0.995, if the meter is within a set geometry range and the flow conditions are within set condition ranges. Although these geometry and flow condition ranges are rather limiting, within these ranges it has been shown that the Venturi meter discharge coefficient is repeatable and therefore calibration is not required. As the cone DP meter is a competitor to the Venturi meter and a candidate for future ISO standards work, it is of interest to plot all available cone DP meter data together to investigate the variation of the discharge coefficient between meters. The meter size restriction here is, for the sake of comparison, held as the same as for the Venturi (i.e. $50 \text{ mm} \le D \le 250 \text{ mm}$) but the beta ratio range has been slightly altered to the common cone DP meter range in industry (i.e. $0.45 \le \beta \le 0.85$). The Reynolds number and pressure limitations of ISO 5167 Part 4 were ignored as they are largely inappropriate to the oil & gas industry. Figure 19 shows all thirty available, non-manufacturer, third party owned cone DP meter data sets plotted on one discharge coefficient vs. Reynolds number graph.

It can be seen in Figure 19 that each individual meter gave data that could be (and was) fitted to give meter flow rate uncertainties of ±0.5% across their respective turndowns. However, there is a wide spread of discharge coefficients between the meters. With the mid discharge coefficient of the spread being approximately a value of 0.8 the spread in discharge coefficient is approximately ±8.5%. There may be some relationship between discharge coefficient, meter diameter, and beta ratio but as yet the authors know of no research in the public domain regarding this. With that said it is evident from Figure 19 that several meters have the same specification and yet have significantly different performances. This is likely due to some relationship between manufacturing tolerance parameters (e.g. angle of cone alignment with pipe centerline) and the discharge coefficient. Currently, it does not seem possible to predict a cone DP meters discharge coefficient to low uncertainty (i.e. the typically desired ±0.5%) and hence to achieve a low flow rate uncertainty each cone DP meter must be individually calibrated across the full Reynolds number range for which it will be used.

4e The Effect of Misaligned Cone Assemblies on a Cone DP Meter Performance

Many cone DP meters are manufactured to a simple technique where the cone and meter body centre lines are not assured to be aligned. It is not unusual for there to be an off set of up to several degrees. Manufacturers state that each meter should be individually calibrated and hence any effect caused by this misalignment can be calibrated out of the metering system. This is true. However, not all cone DP meters are calibrated, at least not across the full Reynolds number range of the application. Furthermore, there is no information in the public domain regarding what variation in discharge coefficient is

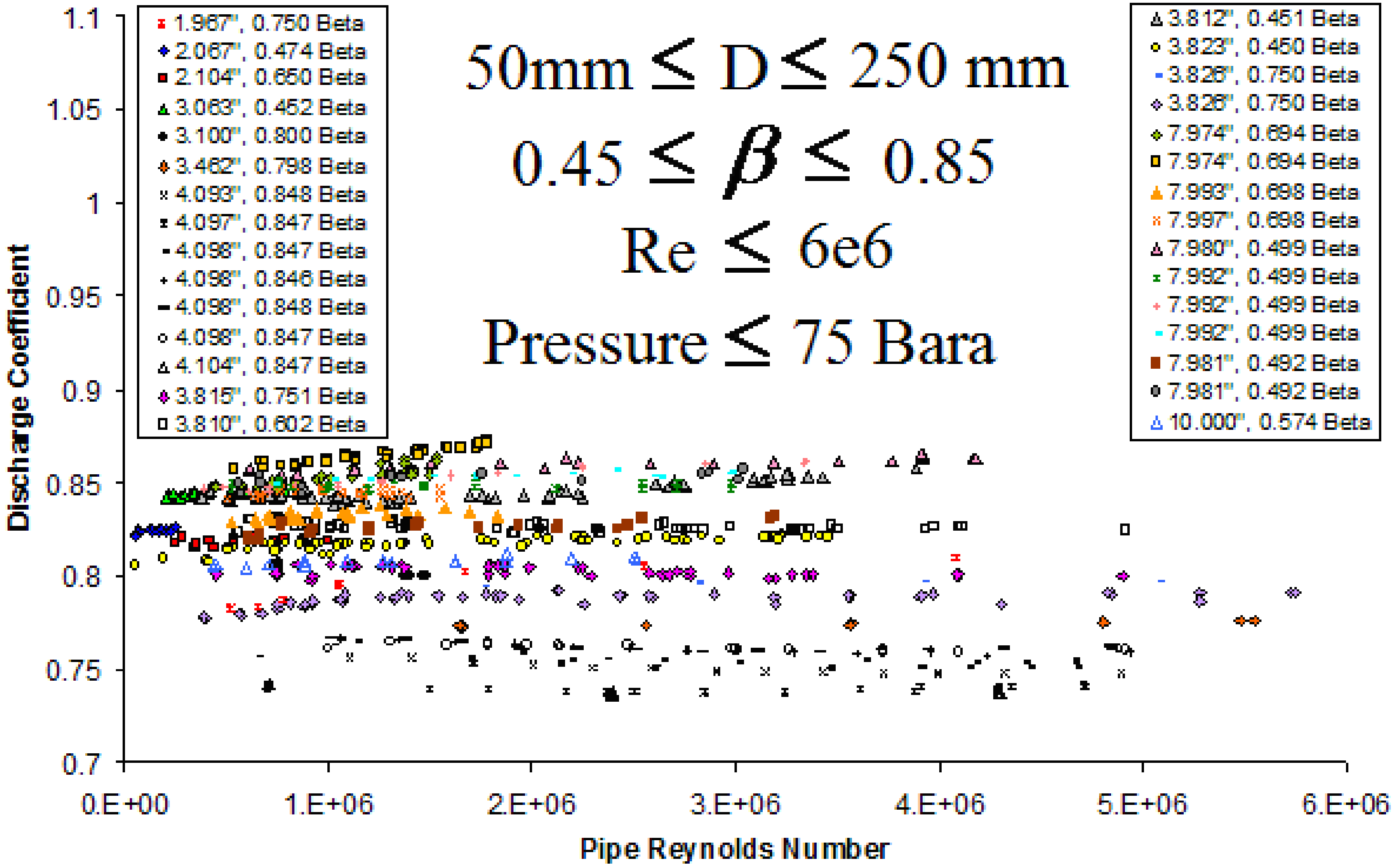

Fig 19. Cone DP meter blinded data sets, Reynolds Number vs. discharge coefficient.

caused by two otherwise identical meters having different cone misalignments. It is widely thought likely that the significant differences in discharge coefficient that can exist between cone DP meters of the same specification (e.g. see Figure 19) is mainly due to this cone misalignment effect. That is, small variations in cone alignments are expected to have a significant effect on the cone DP meters performance.

Deliberately generous tolerances for cone DP meter manufacture (to reduce cost and shorten delivery time) are not the only mechanism that can cause a cone to be misaligned. Mild damage can also occur. The cone is a cantilever[9] with a hollow support. This support is designed to be easily strong enough to hold the cone element under normal conditions. However, if a cone DP meter is dropped, generally mishandled in transit, experiences abnormal flow conditions etc., a small amount of plastic deformation of the support can occur. If the cone alignment shifts from the calibration position it is unlikely that the calibration is still valid.

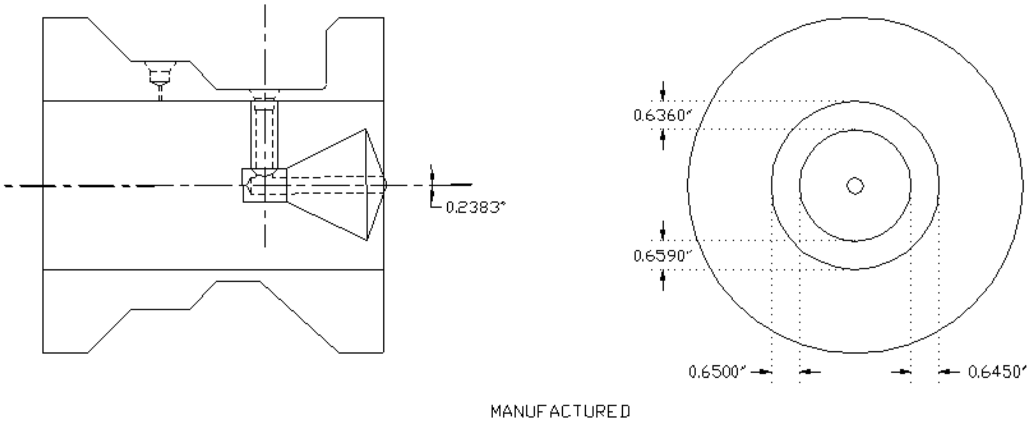

Fig 20. Sketch of the actual 4”, schedule 80, 0.75 beta ratio cone DP meter built.

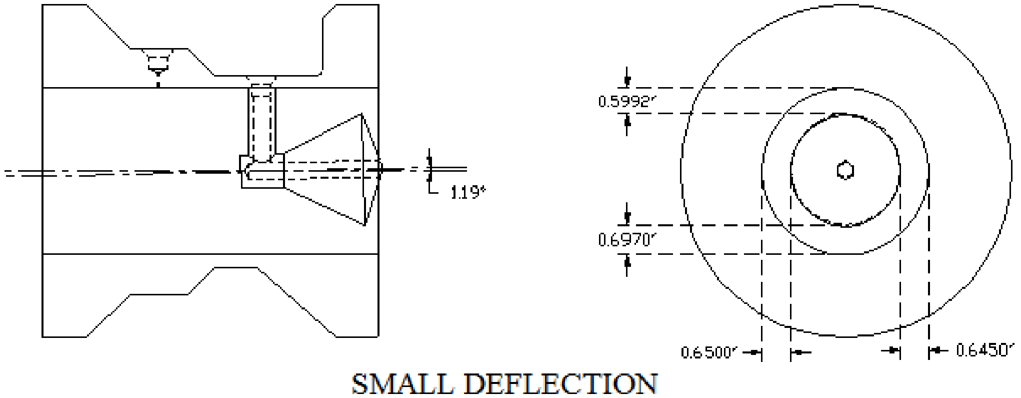

Fig 21. Sketch of the damaged 4”, schedule 80, 0.75 beta ratio cone DP meter

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[9] Some cone DP meters have gussets supporting the cantilever cone design. Gussets increase the cone assemblies strength, stiffness and therefore natural frequency, thereby reduces the likelihood of damage by shock loading or fatigue. Most small cone DP meters (i.e. <6” diameter) have non-gusseted cantilever cone designs due to the difficulty of inserting gussets in small meters. Most large cone DP meters are gusted cantilever cone designs. Gussets are not known to affect meter performance and they do help prevent cone assembly damage considerably.

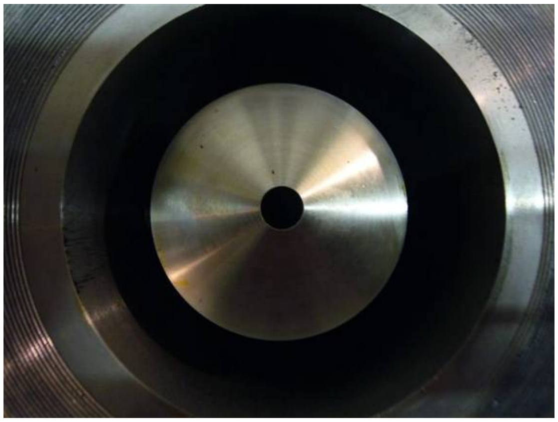

Fig 22. Correctly aligned cone.

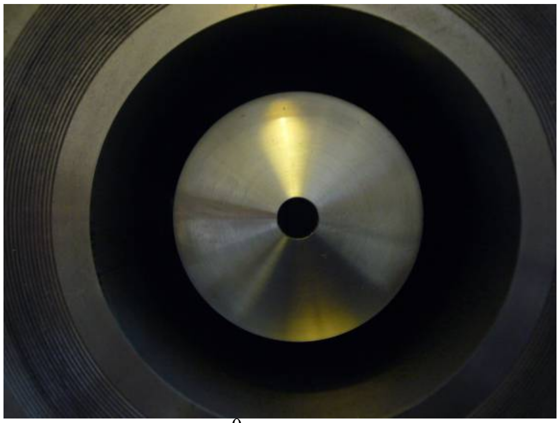

Fig 23. Approx 1^0 misaligned cone.

It is important to know what affect cone misalignment has on a cone DP meters performance. This information can aid understanding on why meters built to the same specification have different discharge coefficients. It would also aid understanding on what level of metering error can be expected if a cone alignment is shifted due to damage after calibration. Therefore, a 4", 0.75 beta ratio cone DP meter with a well centred cone was calibrated and then the cone assembly was deliberately bent out of alignment with the meter body. The damage was slight both to simulate a typical variation of cone alignment between manufactured meters and to simulate typical small damage levels that could go unnoticed by meter operators.

Figure 20 shows the meter as built. The reality of the manufacturing process produces some asymmetry. The cone is misaligned from the meter body centre line by approximately 0.24°. This is a well manufactured meter and this is as close to no deflection as is reasonable for a standard mass produced meter. Figure 22 shows a photograph looking upstream into the meter body (with the cone support at 9 o'clock). No significant deflection is noticeable with the naked eye. Figure 21 shows a sketch of the same meter after the cone assembly was bent upwards to simulate damage due to over stressing of the support. The deflection is very modest at approximately 0.95° (making a cone angle of 1.19° with the meter body centre line). Figure 23 shows the cone DP meter after the cone deflection. Note how small the deflection is to the naked eye and how unlikely it would be that this would be noticed by a standard visual inspection. In fact, this change in cone orientation is small enough to be within the typical manufacturing tolerance of a cone DP meter. That is, two meters built from the same drawing could also have this difference alignment due to manufacturing tolerances alone.

The undamaged meter was calibrated as shown in Figure 24. A linear data fit gave the required ±0.5% uncertainty. Borders at ±0.35% are shown to give perspective on the effect of damage. Figure 24 also shows the cone deflection caused the discharge coefficient to reduce by approximately 0.4%. Thus even small changes in cone alignment seem to significantly affect calibrations. This modest change in cone alignment can be obtained by rough handling of cone DP meters in transit or adverse field conditions. ***It is therefore advisable to treat a cone DP meter as an instrument that requires care and not simply as a pipe spool.*** Measurement of the cone alignment during calibration allows it to be periodically rechecked. Any significant shift indicates recalibration is advisable.

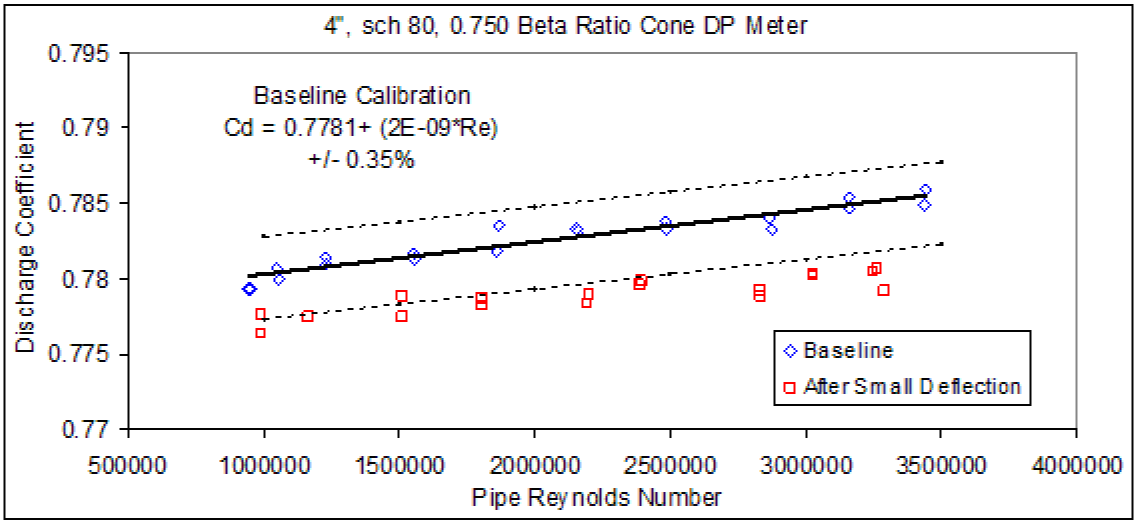

Fig 24. Calibration data for before and after cone deflection.

It is suspected that larger cone / smaller beta ratio cone DP meters will be more susceptible to shifting discharge coefficients as the cone alignment shifts because there is less distance between the beta edge and the meter wall. Hence, there is a more severe change in the meter throat's annular ring shape for a given cone deflection angle. Unfortunately, the heavier the cone is relative to a set support bar size the more susceptible the meter is to damage. Gussets greatly help reduce this problem.

The strength of a cone DP meter without gussets is dependent on the outside diameter, schedule and material specifications of the support bar. Naturally, for a given material, the larger the outside diameter and the higher the schedule (i.e. the smaller the inside bore) the higher the support bars second moment of area and the higher the applied force required before the support bars yield stress is exceeded causing plastic deformation. Therefore, it is advisable for cone DP meters without gussets to be built with as large a support and schedule as possible before the support starts interfering with the cones operation. There is currently little data available on how large a support can be before it starts to interfere with the operation of the cone DP meter.

5. The Potential for Cone DP Meter Sizing Errors

DP meter uncertainty is related to DP transmitter uncertainty. The DP transmitters output has its lowest uncertainty at its upper range limit (or "URL"). It is therefore common practice for a cone DP meter to have the beta ratio sized for a given pipe size, schedule and flow condition range such that the maximum expected DP flow conditions give the URL of the chosen DP transmitter. ***However, this procedure inherently assumes the precise actual maximum DP the meter will see in service can be predicted from discharge coefficient and application flow rate estimates***. In reality, if the actual flow conditions produced a greater DP than the transmitters URL the transmitter is said to be "saturated". A saturated DP transmitter registers the URL and not the actual higher DP. A DP meter can not meter the flow rate correctly with a saturated DP transmitter. Here then, is a very significant potential pitfall to an engineer sizing a DP meter. The estimated DP from a DP meter is found by rearranging equation 1 to give equation 1a:

$$\Delta P = \frac{1}{2\rho}\left(\frac{\dot{m}}{EA_t\varepsilon C_d}\right)^2 \text{ --- (1a)}$$

In order to predict the maximum DP the meter geometry, meter performance and flow conditions must be known. Although in reality, there are manufacturing geometric tolerances, and variations in pressure and temperature from the predicted conditions can change the precise meter geometry, these are all second order effects, and therefore, we can practically consider the meter geometry known. The required geometry terms are the inlet diameter and the beta ratio (i.e. the cone size). From these inputs the velocity of approach, the throat area and geometric terms for the expansibility can be predicted. At the design stage the meter performance is not known and therefore an ***estimated*** constant discharge coefficient is used. The required flow conditions are the flow rate, inlet pressure and the fluids density and isentropic exponent. However, for hydrocarbon production applications the flow conditions are not always precisely known. The reservoir engineers give ***estimated*** flow condition ranges which typically have a few percent uncertainty. Therefore, when designing a cone DP meter to give a maximum DP in service that matches the chosen DP transmitters precise URL two vital pieces of information, i.e. the discharge coefficient and the flow condition range, are being estimated only. Whether the actual maximum DP in service is below, on or exceeds the chosen DP transmitters URL is dependent on the discharge coefficient and the flow condition range estimations. If the actual DP produced when the meter is in service exceeds the DP transmitters URL the meter is not capable of metering the full flow condition range, i.e. it will fail to meter the largest flow rates correctly.

Figure 19 shows that the average discharge coefficient is approximately 0.8 (±8.5%). The scatter is significantly less for set meter diameters and beta ratios. Therefore manufacturers may be able to estimate more precise discharge coefficients for some meter specifications. However, manufacturers still state each cone DP meter requires calibration in order to meet a ±0.5% flow rate uncertainty. Therefore, it is not very likely that any pre-calibration discharge coefficient prediction will be any closer than ±2% to the calibrated value. Furthermore, the authors know from experience that the reservoir engineer flow condition estimates can have uncertainties of several percent.

Cone DP meters with beta ratios set to the fourth decimal place based on these initial discharge coefficient and flow condition estimations are common place. However, in the extremely likely event that these estimations are not precisely correct there is no point choosing a beta ratio to four decimal places. In fact it can give users a false sense of precision and security. Due care should be taken to account for these estimations when choosing a beta ratio as otherwise there is a significant chance that the actual application will saturate the DP transmitter at the applications actual high end flow, therefore making the meter not fit for purpose. An example will highlight this issue:

Worked Example:

A natural gas production company requires a 6”, schedule 80, DP cone meter. The reservoir engineers estimate the pressure will be 28.5 Bara, the temperature 300K, the molecular weight is 20.15, therefore the density will be 24.2 kg/m^3, and the flow rate is 30 MMSCFD. Say the cone DP meter manufacturer estimates a discharge coefficient of 0.80 and as the URL of the transmitter stipulated by the user is say 250"WC (i.e. 62.2 kPa), the manufacturer sets the beta ratio to 0.5844 so as the maximum expected flow conditions produce a DP equal to the URL, i.e. 250.00"WC.

However, after the meter is built and calibrated, say it is found that the discharge coefficient is actually 0.788 (i.e. -1.5% difference). After installation, the actual applications pressure is found to be 28.1 Bara (a -1.4% difference), the temperature is 305K (a +1.7% difference), the molecular weight is 20.25 (a +0.5% difference), therefore the actual density is 23.5kg/ m^3 (a -2.9% difference), and the actual flow rate is 30.3 MMSCFD (a +1% difference). The actual DP produced by the supplied meter is therefore 274.2"WC (i.e. 68.2 kPa). That is, the actual DP is 24.2"WC (6 kPa) greater than the URL of the stipulated DP transmitter. The DP transmitter is saturated. The DP transmitter therefore reads the URL, and typically there is no system alarm stating there is a problem. If this erroneous DP reading is therefore accepted as true, in this example the DP reading of 250"WC predicts a flow rate of 28.97 MMSCFD where as the real flow is 30.3 MMSCFD. That is, the meter would under-read the flow rate by -4.4% or 1.33 MMSCFD. Note that this example is *not* extreme. The predicted to actual parameter variations quoted and the resulting flow rate errors are all modest compared to what could happen in a real application. Furthermore, this kind of metering problem can be difficult to identify as subsequent re-calibrations of the meter with appropriate DP ranges shows no problem. Unfortunately, this is not a trivial theoretical discussion. This design method is common for many generic DP meters.

In this example, to make this meter serviceable (if the problem is ever noticed) a DP transmitter with a larger URL would be required to replace the existing undersized DP transmitter. However, this problem should never be allowed to occur. It can be avoided at the design stage by taking due account of the uncertainties associated with discharge coefficient and flow condition estimations. Therefore, when sizing a cone DP meter (or any DP meter) it is best to set the desired maximum DP at a value lower than the stipulated DP transmitters URL. The actual maximum DP designed for should be down to engineering judgment per application. For example, in this case let us say the engineer played safe and sized the meter to a maximum DP of 220"WC. At the estimated discharge coefficient (0.80) and estimated flow conditions a beta ratio of 0.6006 gives a maximum 220"WC result. However, note that with the discharge coefficient not known to within ±2% at best before calibration there is no real meaning to the last two beta ratio decimal points. Engineers should round up the beta ratio value to the second decimal place. Here, that is a beta ratio of 0.60, giving an estimated maximum DP of 221.1"WC, well below the URL of 250"WC. Now, if this meter was used in the actual field conditions described above the maximum DP would be 242.5"WC, which is still below the applications set URL limit. That is, the saturating of the stipulated DP transmitter would be avoided from the initial design stage and the meter is now fit for purpose.

6. Standardizing the Cone DP Meter Design and ISO Standards

It would be beneficial for industry to have a standard cone DP meter design. Currently, there can be different size cone supports, different orientated upstream pressure tappings relative to the support bar, slightly different cone designs (due to fabrication issues) and different inlet lengths between the inlet of the meter spool and the cone location. Different diameter meters even of the same schedule and beta ratio are not typically geometrically similar by design. It is also common practice to size the beta ratio according to estimated flow conditions up to the fourth decimal place. Therefore, the available public data from cone DP meter calibrations is often not for the same meter design and flow conditions twice. In order for the performance of the cone DP meter to be ready for inclusion in a standard there needs to be massed data sets on the same geometry cone DP meter showing the performance of that design to be reproducible. The phrase "same geometry" includes tight tolerances on the vital dimensions of the meter, and this clearly includes the angle of deviation of the cone to meter centerlines. With the discharge coefficient not being currently predictable to a low uncertainty without calibration the beta ratio needs only to be set to the second decimal place. Furthermore, as there is a possibility that the cone DP meter discharge coefficient is related to the beta ratio (as it is for an orifice plate meter) it may be beneficial for manufacturers to concentrate the beta ratio range to set values. For example, 0.45 to 0.80 beta ratios with 0.05 increments. This, along with geometric similarity, would in the long run allow a better chance of a detailed comparison of the data and give standards organizations a better chance of making a definite statement regards the meters performance. However, for the foreseeable future each cone DP meter must be individually calibrated across the full Reynolds number range of its application.

7. Conclusions

Cone DP meters operate according to the generic DP meter principles. Cone DP meters must be calibrated across an applications full Reynolds number range for the calibration to be valid for that application. It should be noted that most hydrocarbon production applications have flow conditions such that ISO 5167 states a Venturi meter must also, for optimum accuracy, be calibrated across the Venturi meters flow range. Therefore, the cone DP meter and Venturi meter are on par with calibration costs for most hydrocarbon production applications.

The requirement to calibrate a cone DP meter across an applications full Reynolds number range means it is often inappropriate to calibrate the meter in a water flow facility with a limited Reynolds number range and then extrapolate the results to significantly higher Reynolds numbers. Such practice can lead to gross errors in flow measurement.

Analysis of the available data indicates that the current manufacturing tolerance on cone DP meters is not of a level where meters built to the same specification have the same performance. Therefore each individual cone DP meter must be individually calibrated but periodic re-calibration is only required if the operator suspects contamination or damage. However, currently it can be difficult to judge if this is the case while the meter is in service. Therefore, if a meters stated uncertainty rating is of vital importance to the meter operator it can be prudent to periodically re-calibrate the meter.

Owners of cone DP meters should treat the cone DP meter as they would treat any precision instrument – i.e. with care. Initial research indicates that a cone deflection from the meter body centerline of less than 1° was enough to shift the discharge coefficient by approximately 0.4%. Once the cone is deflected, the uncertainty rating is no longer valid and the meter should therefore be re-calibrated. It is concluded that the more firmly the cone is held in place the better.

Care must be taken when sizing a cone DP meter. It is not appropriate to size the beta ratio to four decimal places when the meter performance and application flow range are only estimations. It is prudent to size the beta ratio such that the predicted maximum DP is lower than the DP transmitters URL. This produces a safety factor for when the actual meter performance and application flow range create larger DP's than expected.

It would be premature to attempt to include the cone DP meter in a standard. However, there is abundant evidence that a properly calibrated cone DP meter has a flow rate uncertainty of ±0.5% across a 10:1 flow rate turndown.

Acknowledgments

CEESI thanks Citizens Thermal for releasing multiple cone DP meter data sets for analysis and presentation. CEESI also thanks Cameron and DP Diagnostics for supplying various data sets. Thanks is also given to all companies that had a small numbers of cone DP meter data sets included as part of the massed blinded data set.

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