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Differential Pressure Meters – A Cabinet of Curiosities (and Some Alternative Views on Accepted DP Meter Axioms)

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1. INTRODUCTION

As DP meter technology is well established, recent flow metering conferences have seen little discussion on DP meters. This situation could imply there is no more significant knowledge to be gained in DP meter performance. However, there are still many unknowns and misperceptions regards DP meters. CEESI has compiled a list of such DP meter unknowns, misperceptions, unproven "axioms" and sales pitches that deserve discussion. Although this list is undoubtedly incomplete, there already exists far too much subject matter to cope with in one technical paper. Therefore, in this paper only some of these topics can be discussed. The subject matter produces a wide ranging discussion with surprising findings and conclusions that will be doubtless be considered controversial by some. Nevertheless, as DP meters are still extremely popular and widely used the stimulation of debate on DP meter performance is for the benefit of industry.

2. DO CONE METERS HAVE A HIGHER TURNDOWN THAN ORIFICE METERS?

"The greatest deception men suffer is from their own opinions." - Leonardo da Vinci

To consider this question requires a review of the meaning of turndown, DP meter operating principles, DP transmitter performance and DP meter permanent pressure loss characteristics.

2a) TURNDOWN AND MEANINGFUL TURNDOWN COMPARISONS BETWEEN METERS

Although the flow rate turndown of a meter is important, the meaning of 'turndown' is not universally understood. There is common misunderstanding regards the term that can lead to false impressions when comparing flow meter specifications. Turndown is the ratio of the maximum to minimum flow rates that can be metered *within a stated flow measurement uncertainty*. For example, say a meter has flow range of 100 to 10 units of flow (i.e. 100% to 10% full scale), then the turndown is 100:10. i.e. 10:1. However, often statements such as "… meter A has a turndown of 100:1 while meter B has a turndown of 10:1" produces the false assumption that because Meter A has ten times the turndown of Meter B it must have ten times the flow rate range. However, this is not correct. Meter A has a flow range of 100-1 = 99 units of flow (i.e. a turndown of 100:1). Meter B has a flow range of 100-10 = 90 units of flow (i.e. a turndown of 10:1). Therefore, the difference flow ranges is 99-90 = 9 units of flow. Meter B covers 90/99 (i.e.90.9%) of Meter A's range. *The difference in flow range between 100:1 and 10:1 turndown flow meters is approximately 10% difference, not 10 times difference*!

Many flow meters are stated to have a turndown "up to" x:1. Most applications do not require that stated turndown and do not have flow conditions that allow the meter to utilize that turndown. Pipeline operations tend to cap the velocity at 30 m/s for operational reasons. Most flow meters (DP meters inclusive) can operate at this maximum flow rate. An ability to operate at higher flows is of little practical importance. Turndown comparisons are therefore typically between how **small** a flow rate can be metered. Furthermore, many applications have a low flow cut off below which the meter is off line.

Differences in absolute flow range between meters of different turndowns are not as great as is often assumed. Say Meter 1 has a turndown of x:1 and Meter 2 has a turndown of y:1, where x > y. Let us denote the percentage of Meter 1's absolute flow range that can be covered by Meter 2, when both meters are set to the same full scale flow rate, as $\lambda\%$. Equation 1 shows how this percentage is calculated. Consider an example where Meters 1 & 2 have turndowns

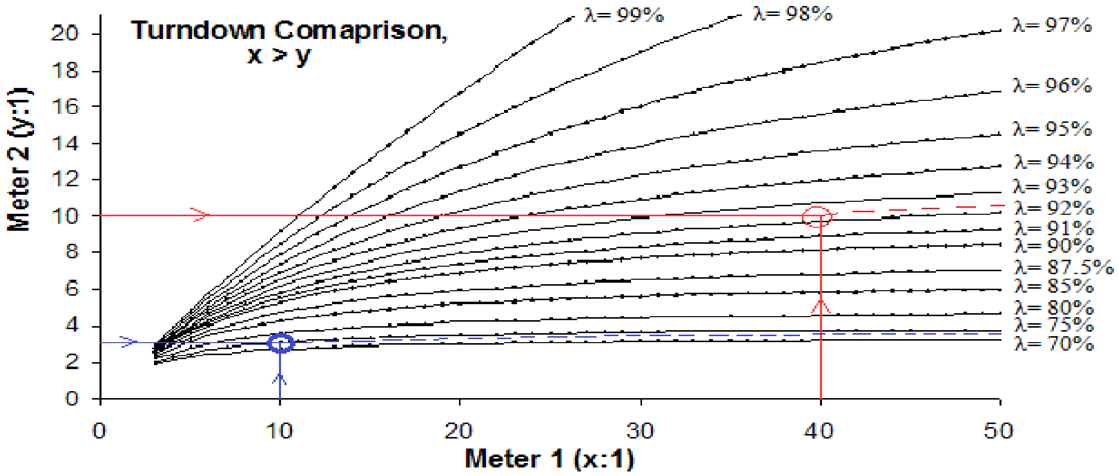

Figure 1. Comparison of Two Flow Meter Turndowns.

40:1 & 10:1 respectively, i.e. $x = 40$ & $y = 10$. The difference in range between the meters is not four times as is often superficially assumed. In reality the 10:1 turndown meter covers 92.3% of the 40:1 meters range (see equation 1a).

$$\lambda\% = \left[\frac{x(y-1)}{y(x-1)}\right] * 100\% \quad \text{--- (1)} \qquad \lambda\% = \left[\frac{40(10-1)}{10(40-1)}\right] * 100\% = 92.31\% \quad \text{-- (1a)}$$

Figure 1 is a graphical representation of equation 1. For any combination of two meters, with the same full scale, the range of the larger turndown (Meter 1) covered by the smaller turndown (Meter 2) is found from lines of constant percentage. The example above is shown. A comparison between 10:1 and 3:1 turndown meters is also shown. This is sometimes the turndown difference advertised between cone and orifice meters respectively. The range difference between such meters is not approximately three times as is often assumed. The 3:1 turndown meter covers approximately 74% of the 10:1 meters range.

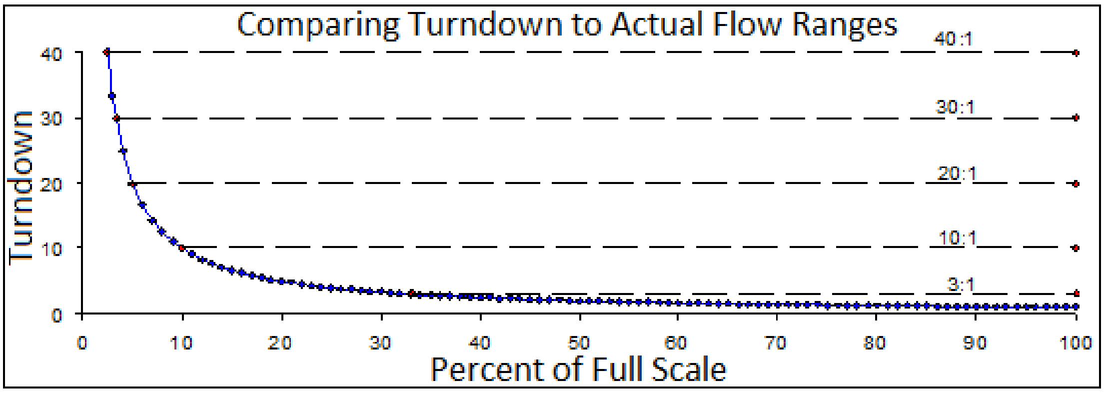

Figure 2. Flow Rate Range to Turndown Comparisons

Figure 2 shows flow rate range vs. turndown. As the turndown increases for a set full scale, a law of diminishing returns exists. For each step increase in turndown an ever smaller actual increase in flow range is attained. It is all too often inferred that a meter with a large turndown has much larger flow range than a meter with a relatively small turndown. However, Figure 2 shows that the flow range difference between any two meters is usually relatively small. In many applications the turndown difference between meters is not as significant as is often suggested. The only important issue with a meters turndown is whether the meter can cover the flow rate range required for a particular application, not what maximum turndown a manufacturer claims.

2b) DIFFERENTIAL PRESSURE METER OPERATION AND TURNDOWN

Orifice and cone meters are both generic DP meters operating on the same physical principles. They use the same generic DP meter flow rate equation, equation 2.

$\dot{m} = EA_t\varepsilon C_d\sqrt{2\rho\Delta P}$ --(2) $\dot{m} = K\sqrt{\Delta P}$ --(2a) $\dot{m} \propto \sqrt{\Delta P}$ --(2b) $K = EA_t\varepsilon C_d\sqrt{2\rho}$ --(3)

Note $\dot{m}$ is the mass flow rate, E and A_t are geometric terms, ε is expansibility (which is a second order effect), C_d is the discharge coefficient (approximately some constant value for any given DP meter), ρ is the fluid density and ΔP is the differential pressure. Therefore, when considering the turndown of orifice and cone meters as they meter a fluid of some set density, it should be noted that: EA_t is a constant set by a meters geometry, ε is a second order effect[1] with a value close to unity and C_d is approximately constant (changing slightly for any DP meter over a large Reynolds number range).

For any DP meter at any given flow condition, equation 2 can be reduced to equation 2a, where "K" (defined by equation 3) is a value that is effectively constant across any DP meters flow range. For *any* given generic DP meter of known discharge coefficient and set fluid density, the flow rate is only proportional to the square root of the DP. Therefore, equation 2b holds true as a fundamental statement about all generic DP meter and the flow rate turndown of any DP meter (orifice and cone meters inclusive) is solely related to the DP turndown that can be generated by a DP meter in a particular application.

2.b.1) <u>DP MEASUREMENT ISSUES</u>

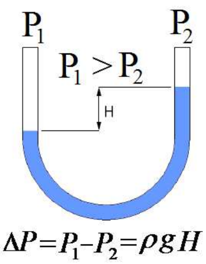

Fig 3a. Manometer.

Fig 3b. Bourdon Gauge.

Fig 3c. Transmitters with DP Meter.

Early DP meter systems read DP's by manometer, Bourdon Gauge or Chart Recorder (mechanical diaphragm) type devices. In practical industrial applications a manometer (see Figure 3a) operator often had limited time to read a fluctuating liquid column height. There were also reading uncertainties associated with parallax issues and small DP's meaning small differences in column heights. Bourdon gauge (see Figure 3b) DP reading uncertainty was dependent on the size of the instrument face, the gradation of the scale, the vibration level on the needle, the calibration interval and the parallax effect. Chart Recorders presented the DP on a chart that was easy to read for high DP's but as the DP's reduced reading an accurate DP became increasingly difficult. Therefore, early methods of DP measurement had a *DP turndown* of approximately 10:1 and hence ***early*** DP meters were said to have a corresponding flow rate turndown (due to equation 2b) of $\sqrt{10}$:1, i.e. ≈ 3:1. Hence, for several generations, standards authors, engineers, technicians, operators etc. have been taught, and taught others in turn, that

[1] Expansibility can be an issue with DP meters turndown if the ΔP becomes large relative to the pressure. However, in most applications this is not a significant issue. In any case, expansibility is similar for all DP meters so this issue can not account for any difference in turndown specifications.

an orifice meters flow rate turndown is 3:1 with the result that over time few questioned that accepted fact (or “axiom”).

The cone meter is a generic DP meter introduced in the 1980’s and marketed as unique new technology. With an image of being fundamentally different to other DP meters it was de-coupled from the historic generic DP meter flow rate turndown specification of 3:1. It has been marketed as a 10:1 (or more) flow rate turndown meter. By the late 1980’s DP’s could be measured by electronic (either analog or increasingly digital) DP transmitter technology (see Figure 3c). Along with more accurate DP measurement across the instrument’s useable range, DP transmitters allow a significantly larger DP range to be measured. This is partly due to a single transmitter measuring a slightly larger DP range than earlier DP measurement systems, but far more significantly, by the use of stacked DP transmitters set to different DP ranges. The advent of electronic DP transmitter technology with variable range settings has therefore very significantly increased the DP reading turndown and as a consequence the flow rate turndown of all DP meters. The orifice meter is still saddled with pre-conceived perceptions and literature declaring the long true (but now very out-dated) statement that it has a flow rate turndown of 3:1. However, cone meters had no such history, and no such literature and pre-conceived perceptions. Hence, cone meter manufacturers were free to quote turndowns they thought were appropriate with the use of electronic DP transmitters, and that they witnessed under testing, i.e. “10:1 or more”.

2.b.2) FIXED MAXIMUM DP’S & DP METER FLOWRATE TURNDOWN

As orifice and cone meters both now use the same modern digital DP transmitters there is no flow rate turndown difference directly due to DP transmitter technology. The flow rate turndown of any generic DP meter is influenced solely by the maximum DP range allowed. Two different DP meter designs with the same DP turndown have the same flow rate turndown as a consequence of the generic DP meter rule stated by equation 2b. A generic DP meter design does not have a fixed turndown, but rather a turndown wholly dictated by the maximum DP range allowed for a particular application.

The smaller a DP the more difficult it is to measure. Hence, even digital DP transmitters have trouble measuring the DP within the required uncertainty below some minimal value dependent on the range of the DP transmitter. However by <2”WC[2] (i.e. approximately 0.5kPa) all DP transmitters (regardless of the upper range limit, or “URL”) have difficultly measuring industrial setting DP’s with accuracy. Hence, even when stacking DP transmitters of different ranges, the minimum reliable DP measurement is set by this practical instrument issue. With the minimum reliable DP measurement set, then the DP range and therefore the flow rate turndown, are set by the choice of the maximum permissible DP. This statement is independent of DP meter design (e.g. orifice meter, cone meter, Venturi meter etc.). Examples are shown in Table 1.

Max DP	Min DP	DP Turndown	Flow Rate Turndown
100”WC / 250mBar	2”WC / 5mBar	100:2 i.e. 50:1	√50:1 i.e. 7:1
200”WC / 500mBar	2”WC / 5mBar	200:2 i.e. 100:1	√100:1 i.e. 10:1
400”WC / 1000mBar	2”WC / 5mBar	400:2 i.e. 200:1	√200:1 i.e. 14:1
1000”WC / 2500mBar	2”WC / 5mBar	1000:2 i.e. 500:1	√500:1 i.e. 22:1

Table 1. Examples of DP Meter Flow Rate Turndown for Set Maximum DP Values.

A DP meter flow rate prediction uncertainty (once **all** uncertainties are accounted for), say “δ%”, is commonly considered to be between 0.7% and 1%. This over-all uncertainty budget is made up of three factors, the uncertainty of the discharge coefficient (say “x%”), the DP reading (say “z%”)

[2] DP meter manufacturers sometimes claim a ΔP minimum of 0.1”WC to maximize the meters turndown specification. Operators sometimes claim a ΔP minimum of 20”WC to avoid significant DP reading induced metering bias. From extensive experience from years of calibrations CEESI considers a reasonable minimum value to be between these extremes at approximately 2”WC (0.5 kPa).

and other miscellaneous factors such as density measurement, expansibility and meter geometry uncertainties (say "y%"). Typically the discharge coefficient uncertainty is said to be 0.5% (e.g. see ISO 5167 [1] for orifice meters). A large allowance for the miscellaneous uncertainty is 0.2%. The overall uncertainty is found from the root mean square of these components. The DP reading uncertainty allowance is therefore 0.84%, i.e.:

$$\delta\% = \sqrt{(x\%)^2 + (y\%)^2 + (z\%)^2} = \sqrt{(0.5)^2 + (0.2)^2 + (z)^2} = 1\% \text{ therefore } z = 0.84\%.$$

Equation 2 shows that the DP is related to the flow rate by a square root. The DP's sensitivity to the flow rate is therefore one half. Hence, the maximum permissible DP uncertainty in order to obtain the required overall flow rate uncertainty is 2*0.84%, i.e. 1.68%.

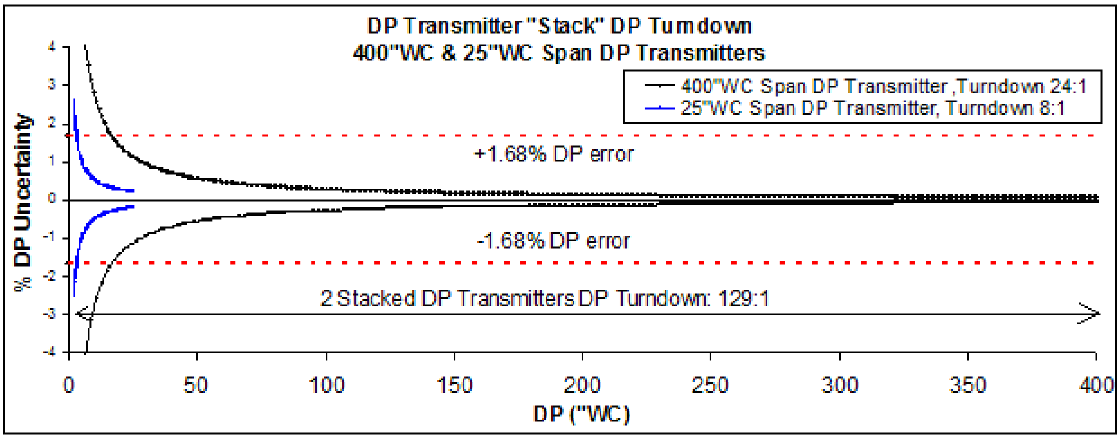

Fig 4. Generic DP Meter DP Turndown Worked Example.

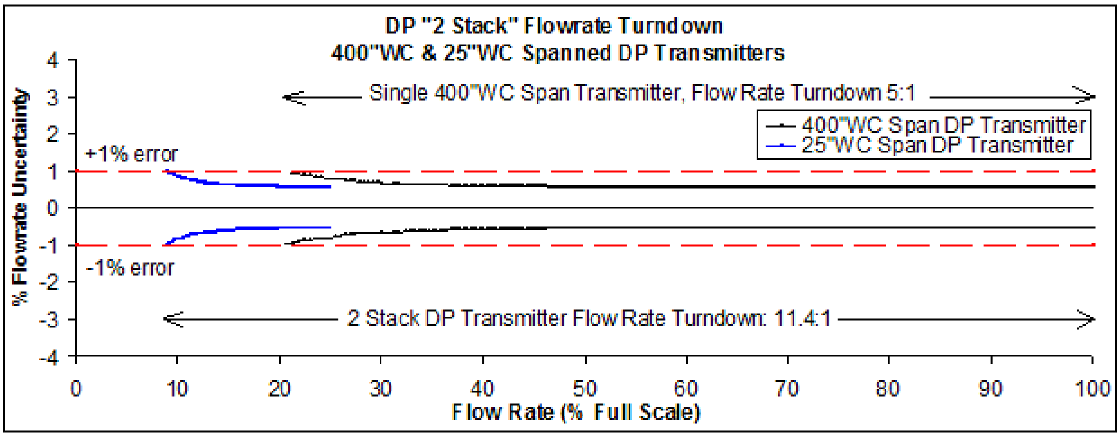

Fig 4a. Generic DP Meter Flow Rate Turndown Worked Example.

Say that an operator allows some application a DP up to 400"WC (i.e. approx. 99kPa). DP transmitters are available where 400"WC is available as the spanned maximum DP. Say the pressure is 250psia and the transmitters experience a 10^0F variation in temperature. At these conditions the DP transmitter (set to an URL of 400"WC) reads the 400"WC with a low DP reading uncertainty of 0.07% (see Figure 4). Reducing the DP's increases the measurement uncertainty until at 16.8"WC the uncertainty is the maximum allowed 1.68%. So the DP turndown is 400"WC:16.8"WC, i.e. a DP turndown of approximately 24:1 and an associated single DP transmitter flow rate turndown of √24:1, i.e. approximately 5:1 (see Figure 4a). However, if we were to add a DP transmitter of a smaller range (i.e. stack DP transmitters) the turndown specification changes significantly. Choosing a second DP transmitter with a URL of 25"WC (i.e.

6.2kPa), which is within the higher DP transmitter's acceptable range, the DP uncertainty at 25"WC is 0.21%. Reducing the DP's increases the measurement uncertainty until at 3.1"WC the uncertainty is the maximum allowed 1.68%. The DP range is now 400"WC to 3.1"WC. i.e. 129:1 (see Figure 4) which corresponds to a flow rate turndown of √129:1, i.e. 11.4:1 (see Figure 4a).

This generic DP meter flow rate turndown example is independent of the type of DP meter. This example applies to both orifice and cone meters. Therefore we see that with modern DP transmitters an orifice meter has the capacity to have a substantially larger flow rate turndown than 3:1. With a single modern DP transmitter a turndown of >3:1 is achievable. If the simple procedure of stacking DP transmitters is carried out then the DP and flow rate turndown is increased considerably. With a two DP transmitter stack a generic DP meter can have a flow rate turndown >10:1. By stacking modern digital DP transmitters an orifice meters turndown is not 3:1 as is so often claimed but >10:1. Likewise we see that the cone meter turndown claims are realistic for stacked DP transmitters. Therefore, the reason a cone meter has a higher advertised turndown than an orifice meter is that the cone meter advertised turndown is the correct modern flow rate turndown of a DP meter (i.e. > 10:1) while much of the old orifice meter literature still cited is out of date and states an incorrect orifice meter turndown (i.e. 3:1).

2.b.3) DP METER FLOW RATE TURNDOWN WITH FIXED MAXIMUM PPL

Operators often set a maximum DP for a given DP meter application. However, in practice the maximum DP created by a DP meter is not as important[3] as the associated permanent pressure loss (or "PPL"). The DP is partially recovered downstream of the meter with only the PPL portion contributing to the operating cost. The generic DP meter PPL is some fraction of the DP. Therefore, setting the maximum allowable PPL for a given meter sets an associated larger maximum DP. As such setting a maximum PPL instead of a maximum traditional DP is an alternative DP turndown and flow rate turndown limiting factor.

$$PLR = \Delta P_{PPL} / \Delta P \quad \text{-- (4)}$$

The Pressure Loss Ratio ("PLR") is defined as the PPL (ΔP_{PPL}) to DP (ΔP_t) ratio (see equation 4). All generic DP meters have a PLR within the range: $0 \le PLR \le 1$. The PLR value for any given DP meter is approximately a constant lying somewhere within this range. However, the PLR value for any DP meter is not well defined in the literature. ISO 5167-2 [1] cites a theoretical PLR prediction for orifice meters (by Urner [2]) *with no associated uncertainty guarantee*. ISO 5167-4 [3] gives a notably imprecise PLR prediction for Venturi meters that is the large range of $0.05 \le PLR \le 0.20$. The only publicly available cone meter PLR equation is given in one manufacturer's literature. No proof (i.e. no independent data) is presented and no associated uncertainty is offered. It is therefore difficult to predict *any* particular DP meters geometries PLR with any precision. As such it is difficult to predict a precise PPL for any given DP. Hence, operators tend to state a maximum allowable DP rather than a maximum allowable PPL. By setting a maximum DP, as $PLR \le 1$, they are effectively guaranteeing the PPL will at least not exceed the set maximum DP. This typical procedure does not produce the applications maximum allowable PPL at the maximum flow rate. It guarantees a PPL less than the maximum allowed, and therefore a lower maximum DP and a lower flow rate turndown than is possible for the DP meter in that application.

If the operator wishes to be more sophisticated it is possible to maximize the DP meter flow rate turndown by matching the maximum DP to the maximum allowed PPL. To do this the DP meters PLR characteristics must be well known. In this optimum generic DP meter flow rate turndown design case, the flow rate turndown is dictated by the DP turndown, which is dictated by the maximum allowable DP, which is dictated by the combination of the operators maximum allowable PPL and the DP meters PLR. That is, for any given DP meter **the maximum possible flow rate turndown is dictated by the applications maximum acceptable PPL and the meters PLR characteristics**. Therefore, in order to set the maximum flow rate turndown of a DP

[3] The DP does require checking against the minimum ΔP/P value allowed by the expansibility equation.

meter it is necessary to know the meters PLR with some precision. It is therefore ***remarkable*** that in 2012 so little is known regards the PLR of even the most common DP meter designs. The most widely used flow meter designs in history has one of its most important specifications, i.e. the flow rate turndown, dictated by the PLR, and industry still does not know what the precise PLR value of any common DP meter design actually is!? Hence, it is now necessary to set uncertainty estimations to DP meter PLR predictions.

2.b.3.1) THE PLR OF AN ORIFICE PLATE METER

ISO 5167-2 [1] offers a theoretical prediction (by Urner [2]) for the orifice meter's PLR. This is reproduced here as equation 5. ISO offers no associated uncertainty, stating instead that the equation is "approximate". The equation is predicting that the orifice meter PLR is dependent on both the beta ratio (β), i.e. the square root of the orifice to inlet area ratio (as shown in equation 9) and the discharge coefficient. However, this equation indicates that the orifice meter PLR is significantly more sensitive to the beta ratio than discharge coefficient. The authors can find no independent analysis of the accuracy of Urner's PLR prediction.

$$PLR = \frac{\sqrt{1-\left\{\beta^4\left(1-C_d^2\right)\right\}}-C_d\beta^2}{\sqrt{1-\left\{\beta^4\left(1-C_d^2\right)\right\}}+C_d\beta^2} \quad \text{--- (5)}$$

Urner's orifice meter PLR equation (equation 5) predicts the pressure loss between one pipe diameter (1D) upstream and six diameters (6D) downstream of the orifice plate. Figure 5 shows a reproduction of the ISO 5167-2 [1] sketch with significant modifications to emphasis certain relevant points to this discussion. Note that in Figure 5 the number system represents:

1. Upstream flange pressure tap plane
2. Low pressure flange pressure tap plane
3. Plane of "vena contracta"
4. Re-circulation zones
5. Flange Pressure taps
6. Pressure tap 1D upstream of plate
7. Pressure tap 6D downstream of plate
8. Pressure distribution on wall of meter run.

Below the diagram of the meter in Figure 5 is a representation of the pressure field through the meter. Unfortunately, while the unproven orifice meter PLR theoretical prediction is for the PPL predicted for the 1D upstream to 6D downstream pressure taps, most of the modern orifice meter data comes from flange tap orifice meters. Flange tapped orifice meters (as drawn in Figure 5) have the inlet pressure tap closer to the plate than 1D. As a result, the inlet pressure is somewhat affected by the presence of the plate. This effect is shown in Figure 5. The actual "DP" read by flange taps is denoted by ΔP_t. The DP created by the plates influence between 1D and the upstream flange tap is denoted as ΔP^*. Therefore, the "PPL" read from flange taps and 6D downstream is denoted by ΔP^*_{PPL}. The PPL that would have been read if the upstream pressure tap was at 1D instead of at the inlet flange is denoted as ΔP_{PPL}. Hence, $\Delta P^*_{PPL} > \Delta P_{PPL}$ and there is an inherent bias in the data when using the flange tap data to check the Urner PLR

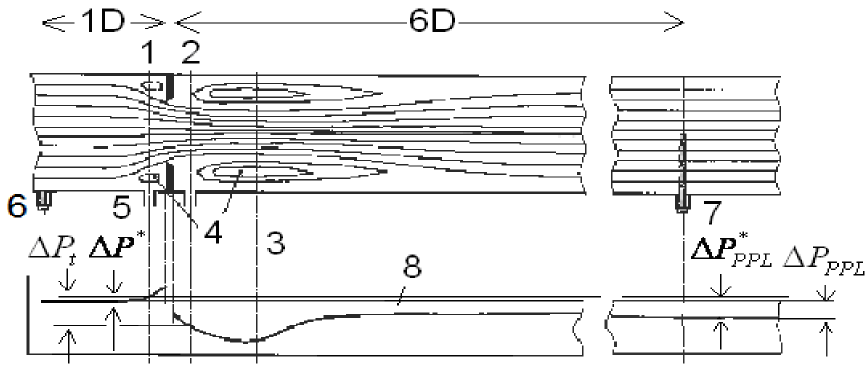

Fig 5. Modification of the ISO 5167-2 sketch of the Orifice Meter and Pressure Field.

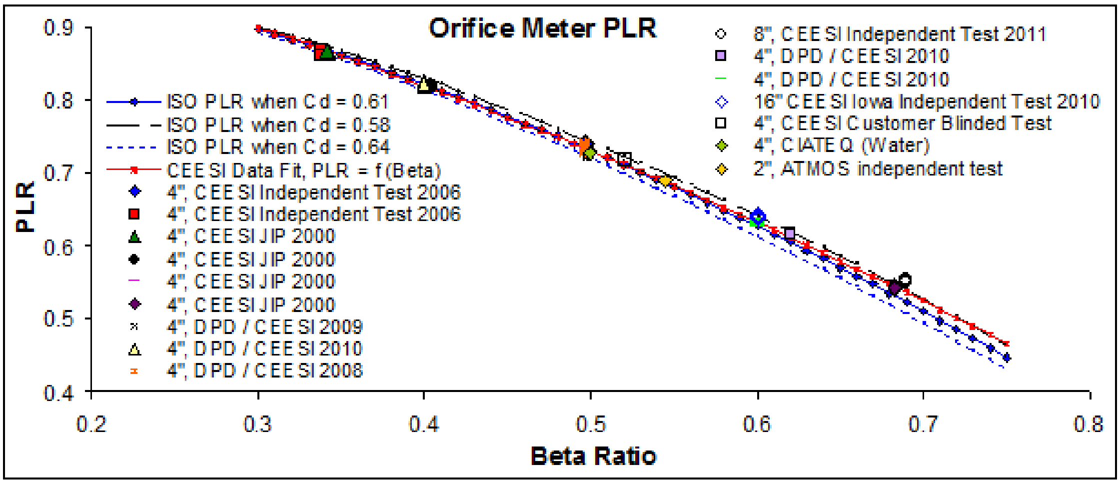

Fig 6. Comparison of the ISO Orifice Meter PLR Prediction with Independent Data.

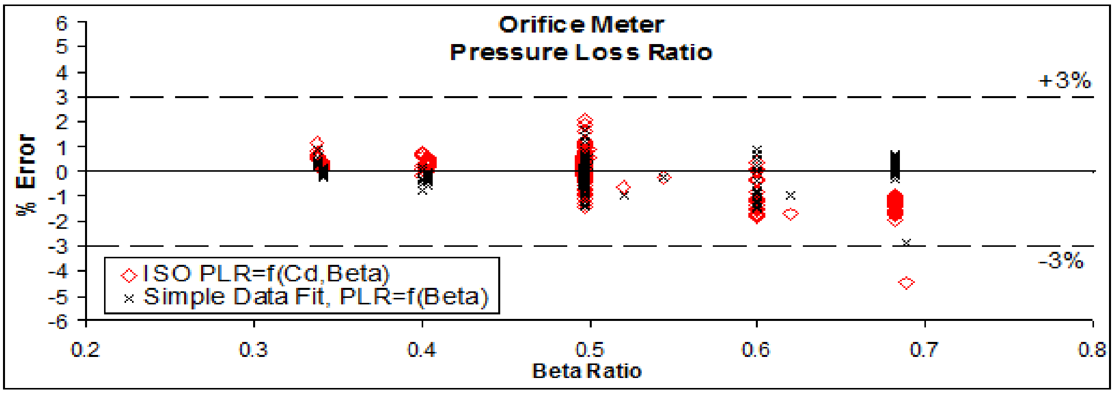

Fig 7. Comparison of the ISO Orifice Meter PLR Prediction with Independent Data.

$$PLR = 1.655 + \left(-0.564 * \exp(\beta)\right) \text{ --- (6)}$$

prediction. However, Figure 5 is not drawn to scale. Although the upstream tap position induces a bias when comparing the available flange tap orifice meter data with the Urner PLR prediction, the authors suspected this bias would be small. Hence, such a comparison has been made to validate the Urner PLR orifice meter equation with an uncertainty statement.

Figure 6 shows the result of comparing the Urner PLR equation to the available flange tap orifice meter data. The Urner PLR prediction across a range of beta ratios ($0.33 \le \beta \le 0.69$) is shown for three discharge coefficients that span a reasonable range for the orifice meter (according to ISO 5167 [2]). It is clear that the PLR prediction is far more sensitive to beta ratio than discharge coefficient. The PLR found from sixteen different flange tap orifice meter data sets have also been plotted. This consists of results from four different test labs, using six different test stands, a range of orifice meter sizes from 2" to 16", paddle plate, single and double chamber orifice plate meters, test fluids of air, water and natural gas at various Reynolds numbers, pressures, and DP ranges. The results clearly match the Urner PLR prediction very closely.

Figure 7 shows the percentage deviation of this data to the Urner PLR prediction. The Urner PLR equation predicted the read "PLR" to within an uncertainty of 3% at a 95% confidence level. However, it was noted that at higher beta ratios (i.e. $\beta > 0.55$) the Urner PLR equation tended to slightly under predict the results. As the discharge coefficient influence on PLR was so small compared to the beta ratio influence it was noted that a simple approximate data fit for PLR = f(β)

could be appropriate. The resulting fit is shown as equation 6. The uncertainty is still 3% at a 95% confidence level, however the beta ratio bias at higher beta ratios has been removed.

Equation 6 represents a quick data fit to the available data. It is not claimed that this equation is the most precise data fit that could be created on this data set. Nevertheless, this simple approximation is still a very close fit to the Urner theoretical ISO PLR prediction of equation 5. The Urner PLR equation is remarkably accurate, especially considering it is from a theoretical derivation. The orifice meter PLR can be predicted by either to 3% at 95% confidence.

2.b.3.2) THE PLR OF A CONE METER

The authors know of one public cone meter PLR equation. It is a manufacturer's claim and has no associated uncertainty statement. It has not been independently verified. CEESI therefore gathered cone meter data sets with recorded PPL. This data comes from CEESI internal research and blinded (with permission) 3rd party data. These data sets were not recorded for this research and therefore the downstream pressure taps are in different positions. There is no agreed minimum distance downstream of a cone meter where pressure recovery is considered complete. (This is different to the orifice meter where 6D is the ISO stated distance, as shown in Figure 5.) In the data sets available (from cone meters from three different manufacturers tested at different test facilities) the downstream pressure tap was located in various positions between 2.5D to 6D downstream of the rear of the cone. The data covers 2" to 8" cone meters, 0.45 ≤ β ≤ 0.75 (i.e. a reasonable range for industries cone sizes), air and natural gas over a range of pressures, DP's and Reynolds numbers. A minimum PPL of 5"WC (12.5 mBar) was set to avoid DP measurement uncertainty skewing the data.

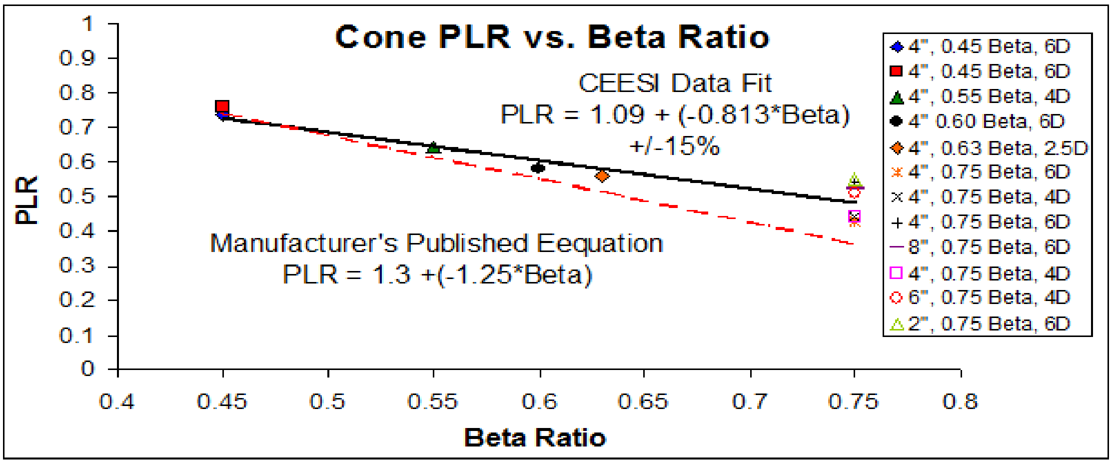

Figure 8. Comparison of the Cone Meter PLR Predictions with Available Cone Meter Test Data.

Figure 8 shows twelve cone meters PLR vs. β data sets. Surprisingly, there appears to be little difference in the results obtained between the downstream pressure tap positions. Seven of the twelve cone meters have a beta ratio of 0.75. However, across the beta ratio range there seems to be a general trend where a simple linear data fit will represent the PLR data well. The 0.75 beta data has significant scatter. However, within this 0.75 beta ratio data surprisingly there is no obvious correlation between the downstream pressure tap position and the PLR variation. A CEESI data fit (equation 7) has a large uncertainty value of 15% to account for the scatter at the 0.75 beta ratio limit, although the other data does fit considerably better. Considering there are only five non 0.75 beta ratio cone meter data sets available it is deemed reasonable to keep the uncertainty at this level until more data sets confirm or alter this data fit.

$$PLR = 1.09 + (-0.813 * \beta) \quad \text{--- (7)} \qquad PLR = 1.3 + (-1.25\beta) \quad \text{--- (8)}$$

Figure 8 also shows the published manufacturer cone meter PLR (equation 8). Although this equation and the CEESI data fit are reasonably close it can be seen that equation 8 predicts lower PLR values at higher beta ratios than the CEESI equation. Therefore, the PLR of a cone meter is still only approximately known. With no cone meter standard different cone meters have different geometries. It is therefore still appropriate to calibrate each cone meter to find both the discharge coefficient, and if required the PLR. The above cone meter PLR equations only give an approximation of the PLR to meter designers.

2b.3.3) COMPARING THE FLOW RATE TURNDOWN & PPL OF ORIFICE & CONE METERS

"A man should look for what is, and not for what he thinks should be" – Albert Einstein

Figure 9 shows the ISO 5167 PLR predictions for a Venturi meter and an orifice meter (at Cd = 0.6). It also shows the manufacturer published cone meter PLR and new CEESI estimation of the cone meter PLR. The ISO Venturi meter PLR is also approximate and an investigation into its precise value is one of the many important topics omitted from this paper due to space (and lack of data). However, it is known that the ISO Venturi meter prediction of $0.05 \le PLR \le 0.20$ holds for multiple independent data sets owned by many organizations. Therefore regardless of the relative imprecision of the Venturi meter PLR prediction the value is still significantly less than the cone and orifice PLR values. The orifice meter has the highest PLR. It is evident that regardless of which cone meter PLR equation is considered correct, the cone meter PLR is only slightly less than that of the orifice meter. This has consequences when it comes to comparing the PPL penalty and the associated maximum flow rate turndown of cone and orifice meters.

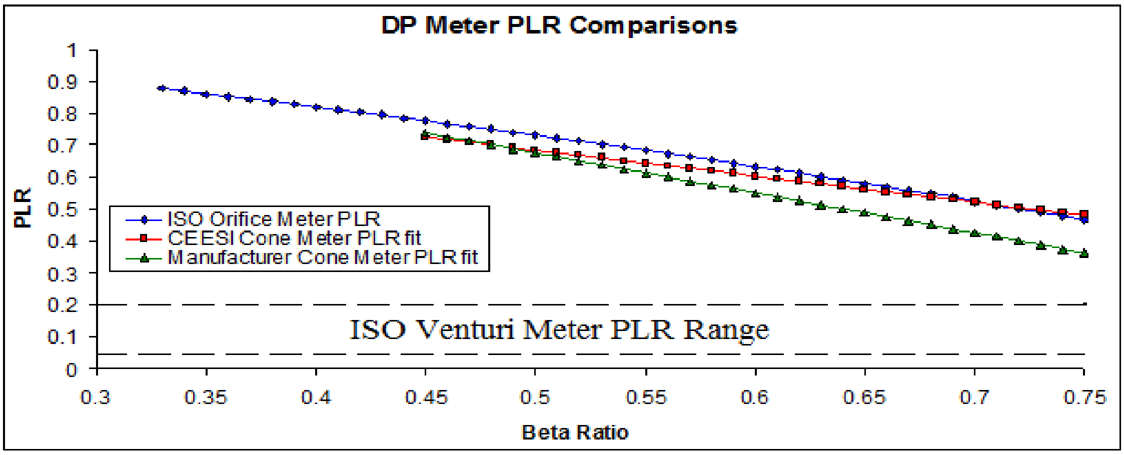

Figure 9. DP Meter PLR Values for Various Beta Ratios.

A DP meter must be "sized" for a given application. As the inlet diameter is the pipe diameter, "sizing" practically means calculating the appropriate beta ratio for a given application. There is a maximum predicted flow rate and an expected fluid type at set flow conditions. For orifice meters the discharge coefficient is set by ISO 5167 (approximately 0.6) or approximated by set values for the cone (typically some value close to 0.8) and the Venturi (typically some value close to 0.995). The expansibility is approximately unity (although precisely calculated during the sizing). The "sizing" calculates the beta ratio required to produce the desired maximum DP at a predicted maximum flow rate and flow conditions. Figure 10 shows the generic DP meter flow rate equation (i.e. equation 2) with comments regards each term with respect to the sizing procedure.

The operator will usually dictate either a maximum DP or PPL. ***These two different scenarios require different beta ratios.*** If a maximum DP is set then the turndown of any set DP meter is also set along with an associated beta ratio. To calculate the appropriate beta ratio for a set maximum DP substitute equation 9a and 10 into equation 2 and re-arrange to create equation 2c. (Note A in equation 9 is the meter inlet area.) All terms on the right hand side of this equation are

Geometry Terms Variable by Varying Beta Ratio

discharge coefficient fixed by meter type

$$\dot{m} = EA_t \, \varepsilon \, C_d \sqrt{2 \rho \Delta P}$$

max flow fixed by application

expansibility ≈ 1

density fixed by application

max DP fixed by operator

Figure 10. Generic DP meter flow rate equation (2) with comments regards the sizing procedure.

fixed[4] by the pipe size, meter characteristics, the applications flow conditions and the maximum DP allowed. Equation 2c is iterated to find the beta ratio. <u>The smaller the discharge coefficient the larger the beta ratio required to solve equation 2c</u>. That is for any set application:

$$C_{d,orifice} < C_{d,cone} < C_{d,Venturi} \quad \text{therefore} \quad \beta_{orifice} > \beta_{cone} > \beta_{Venturi} .$$

Regardless, if any two DP meter designs (even with different beta ratios) have the same fixed maximum DP they have the same DP turndown and therefore the same flow rate turndown. However, if the operator states a maximum PPL (*instead of* a maximum DP) then the DP turndown of any DP meter can be optimized. Here the beta ratio is found by substituting equation 4 into equation 2c to create equation 2d. The left hand side of the equation requires that the PLR vs. beta ratio (β) relationship be known. We must substitute into equation 2d an appropriate PLR vs. β equation. The resulting iteration solves for beta ratio and the associated PLR allowing the associated maximum DP to be derived for the set PPL. As the minimum DP is set (at say, 2"WC) we have found the maximum DP and flow rate turndown of that DP meter in that application. A fixed maximum PPL application has a turndown dependent on a combination of the beta ratio and the PLR vs. β relationship. We are now in a position to directly compare the maximum potential turndown of different DP meters.

$\beta = \sqrt{A_t / A}$ -- (9) $\quad A_t = A\beta^2$ -- (9a) $\quad E = 1 \big/ \sqrt{1-\beta^4}$ -- (10) $\quad PLR = \Delta P_{PPL} / \Delta P$ -- (4)

Iterate Equation 2c to find for set DP:

$$\boxed{\frac{\beta^2}{\sqrt{\left(1-\beta^4\right)}} = \frac{\dot{m}}{A \varepsilon C_d \sqrt{2 \rho \Delta P}}} \text{ --- (2c)}$$

Iterate Equation 2cd to find for set PPL:

$$\boxed{\frac{\beta^2}{\sqrt{PLR \left(1-\beta^4\right)}} = \frac{\dot{m}}{A \varepsilon C_d \sqrt{2 \rho \Delta P_{PPL}}}} \text{ --- (2d)}$$

<u>Example</u>: A 6", sch 80 pipe has conditions 20 Bar(a) and 300K with a natural gas at density 14.5 kg/m^3. The maximum flow expected will be 7.3 kg/s (i.e. 30 m/s, or 30 MMSCFD) and a flow rate turndown of say 10:1 is required. The operator may demand a) a maximum DP or b) a maximum PPL. Let us consider the scenarios of a maximum DP of 250"WC (≈ 620 mBar) or a maximum PPL of say 200"WC (≈ 500 mBar). Can an orifice, cone or Venturi meter meet this specification?

2.b.3.3.a) MAXIMUM PERMISSIBLE DP 250"WC (I.E. 620 mBAR)

A useful DP range of 250"WC to 2"WC produces a DP turndown of 250"WC:2"WC, i.e. 125:1, and a generic DP meter flow rate turndown[5] of √125:1, i.e. approximately 11:1. Therefore, all generic DP meters with a DP transmitter stack can cover this applications flow rate turndown.

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[4] This is precisely true of liquid flows, as $\varepsilon = 1$. For gases this is a simplification as $\varepsilon = f\left(\beta, \kappa, P, \Delta P\right)$, where k is the isentropic exponent. In real sizing procedures this is accounted for during the sizing.

An orifice meter (with a discharge coefficient set by ISO 5167) requires a beta ratio of 0.694 to produce a maximum DP of 250"WC at these conditions. Equation 6 states the corresponding PLR is 0.53 meaning the associated maximum PPL is 132"WC.

A cone meter (with a discharge coefficient set at 0.8) requires a beta ratio of 0.617 to produce a maximum DP of 250"WC at these conditions. If we accept Equation 8 the corresponding PLR is 0.53 meaning the associated maximum PPL is also 132"WC. If we accept Equation 7 the corresponding PLR is 0.59 meaning the associated maximum PPL is 147"WC.

A Venturi meter (with a discharge coefficient set at 0.995) requires a beta ratio of 0.560 to produce a maximum DP of 250"WC at these conditions. ISO states a Venturi meters PLR is within the range of $0.05 \le PLR \le 0.20$ (regardless of the beta ratio[6]). If we assume the poorest possible performance of a PLR at 0.2 the associated maximum PPL is 50"WC.

As would be expected, the Venturi meter has the lowest PPL for the set maximum DP. However, the comparison of the orifice and cone meter is more interesting. A cone meter typically has a slightly lower PLR than an orifice meter *for a given beta ratio*. However, for any set flow meter application the orifice meter beta ratio is sized larger than a cone meter beta ratio (due to the orifice meter having the lower discharge coefficient). Therefore, comparing the PLR for a given beta ratio gives a false impression about the relative PPL cost of the meters. The perceived PPL cost disadvantage of an orifice meter over a cone meter due to its larger PLR value at a set beta ratio is off-set by the orifice meter having a larger beta ratio for a given flow application. In this worked example, using the orifice meter PLR fit (equation 6) and the cone meter manufacturers PLR fit (equation 8), we discover that for this set maximum DP case the orifice and the cone meters have effectively the same PLR and PPL values. That is, **the widely held axiom that a cone meter has a lower PPL than an orifice meter is not always true**. This result is counter intuitive and not widely understood in the flow metering community.

2.b.3.3.b) SET MAXIMUM PPL OF 200"WC (≈ 500 mBAR)

In commercial orifice meter calculations the discharge coefficient, expansibility and PLR would all be precisely calculated by the appropriate equations. For this example for simplicity we can assume a discharge coefficient value of 0.6, an expansibility of unity and the PLR predicted by equation 6 respectively. Noting that 1"WC = 248.64 Pa, Equation 2d becomes:

$$\frac{\beta^2}{\sqrt{\{1.655+[-0.564\exp(\beta)]\} \ *(1-\beta^4)}} = \frac{7.3}{(0.01682)*1*0.6*\sqrt{2*14.46*(200*248.64)}} = 0.602$$

Iteration of this equation produces the result, β = 0.647 & PLR = 0.58 (from equation 6). Therefore, as we set the max PPL at 200"WC, from equation 4 we have found that the max allowable DP to keep within the allowable PPL is 342"WC. Therefore we have a DP turndown of 342"WC:2"WC, i.e. 171:1 which is flow rate turndown of √171:1, i.e. 13:1.

In commercial cone meter calculations the expansibility and PLR would be precisely calculated by the appropriate equations. In this example the discharge coefficient is set at 0.8 and for simplicity expansibility is approximated at unity. Let us assume here that the cone meter manufacturers PLR prediction (equation 8) is correct. Equation 2d becomes:

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[5] This example is for a set beta ratio. Orifice meter fittings allow different orifice plate beta ratios to be selected. If an application's flow rate deteriorates slowly over time (e.g. an ageing well) then this ability can allow one orifice meter fitting with a set DP range to have a **very** large turndown (>50:1).

[6] ISO 5167-4 makes some further, yet limited, guidance comments in Annex C. Miller [4] also comments on the Venturi meter PLR vs. β relationship. However, the ISO main documents statement of $0.05 \le PLR \le 0.2$ across the beta ratio range is the only statement in the main body of the standards.

$$\frac{\beta^2}{\sqrt{\{1.3+[-1.25\beta]\} * (1-\beta^4)}} = \frac{7.3}{(0.01682)*1*0.8*\sqrt{2*14.46*(200*248.64)}} = 0.452$$

Iteration of this equation produces the result, β = 0.572 & PLR = 0.59 (from equation 8). As we set the max PPL at 200"WC, from equation 4 we have found that the max DP to keep within the allowable PPL is 342"WC. Therefore we have a DP turndown of 342"WC : 2"WC, i.e. 171:1 which is flow rate turndown of √171:1, i.e. 13:1.

For Venturi meters the discharge coefficient is often approximated as 0.995 while the PLR is 0.2 at most. The Venturi meter therefore produces considerably higher DP's than orifice or cone meters before any PPL limit is reached. The approximation of expansibility as unity is therefore less valid in this Venturi meter example than it is in the above orifice and cone meter examples. The following example therefore applies the adiabatic expansibility prediction. This expansibility equation is relatively complicated and also dependent on the beta ratio. The details of this addition are outside the scope of this paper (however in this example the expansibility was found to be 0.923). Equation 2d therefore becomes:

$$\frac{\beta^2}{\sqrt{0.2*(1-\beta^4)}} = \frac{7.3}{(0.01682)*0.923*0.995*\sqrt{2*14.46*(200*248.64)}} = 0.393$$

Iteration of this equation produces the result, β = 0.417 & PLR = 0.20 (from ISO 5167-4). Therefore, as we set the max PPL at 200"WC, from equation 4 we have found that the max allowable DP to keep within the allowable PPL is 1000"WC. Therefore we have a DP turndown of 1000"WC:2"WC, i.e. 500:1 which is flow rate turndown of √500:1, i.e. 22:1.

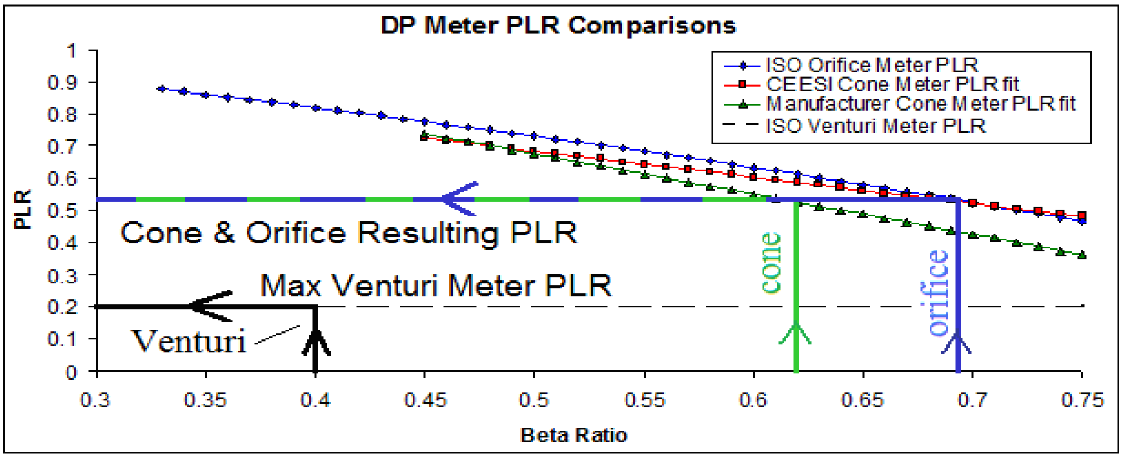

Figure 9a. DP Meter PLR Values for Various Beta Ratios with Results of Worked Example.

The set PPL worked example results are shown in Figure 9a. Using the standard sizing methodology for generic DP meters the orifice meter is sized to have larger beta ratio than a cone meter. The respective PLR predictions therefore produce similar PLR values for the different beta ratios. As there is a fixed maximum PPL and the same PLR, both the orifice and cone meters have the same maximum DP of 342"WC and hence the same DP turndown of 171:1, and the same optimized flow rate turndown of 13:1. The cone meter manufacturer claims of a flow rate turndown of > 10:1 are met, while the orifice meter flow rate turndown is found to be substantially greater than the commonly stated 3:1. It should be noted that ***the widely held axiom that a cone meter has a significantly greater flow rate turndown than an orifice meter is false.***

The maximum PPL produced should be more important to operators than a maximum DP. The DP gets partially recovered while the PPL is that portion which is irrevocably lost. The PPL is an operating cost of the meter and therefore important. ***Setting a DP meter to produce a***

maximum allowable PPL does not just guarantee a limitation of PPL and associated operating costs, it produces the meters maximum potential turndown. However, with limited DP meter PLR research and the existing PLR predictions having no uncertainty statements it is difficult to set a DP meter to a given maximum PPL. Low PLR prediction uncertainty is very important. As such, it is curious why so little attention has been paid to DP meter PLR prediction research!?

2.c) COMMENTS ON VENTURI METERS AND SURGE FLOW

In some applications meters can be periodically exposed to unexpected surge flow that exceeds the maximum design flow rate. It is useful for a meter to not only survive the surge but to continue to operate correctly. Many meters are set to 100% full scale at 30 m/s (100 ft/s). Can a Venturi meter measure a larger surge flow rate? In the example above the meter is sized to produce 1000"WC (2.5 bar) at the maximum flow of 7.3 kg/s (i.e. 30 MMSCFD or 30 m/s). There are DP transmitters on the market with large URL values so DP instrumentation is no barrier. The maximum flow rate of a Venturi meter is set by the limit of the adiabatic expansion equation and the calibrated range of the discharge coefficient. However, few meters (of any design) are calibrated to surge flow rates (and if they were so could a Venturi meter be). Many flow meters extrapolate calibration data during surge flow operation. The limit of the Venturi meter surge flow range could be set at the adiabatic expansibilty equation limit, i.e. $P_2/ P_1 \geq 0.75$, where P_2 is the throat pressure (P_2) and P_1 is the inlet pressure. In this example the line pressure (P_1) is 20 Bar so the minimum throat pressure (P_2) allowed is 15 Bar. This is a DP of 5 Bar (2000"WC). In this example it takes 9.4 kg/s (i.e. 38.6 MMSCFD or 38 m/s) for the 6", 0.417 beta ratio Venturi meter to produce 2000"WC. That is 28% over-speed. The PPL will be ≤ 400"WC (at PLR ≤ 0.2) but during surge flow PPL is not typically a major concern. Also note that Venturi meters are very sturdy flow meters. Therefore, to prepare a Venturi meter for surge events all that is required is to add a high URL DP transmitter to the DP transmitter stack.

This Venturi meter application could be made to have better surge flow capability. If the operators were more concerned about surge flow than high accuracy at the very low end of the flow range, the Venturi meter could have a selected beta ratio of 0.5 instead of 0.417. This would produce a maximum DP of approximately 426"WC at the full scale flow rate of 30 MMSCFD, i.e. a DP turndown of 426"WC:2"WC (i.e. a 213:1) and a flow rate turndown of √213:1 or 14.6:1. This Venturi can meter flow over a 100% to 7% of full scale range. Although there is only a small change in the normal range (i.e. the low flow has increased from 4.5% to 7% full scale), the surge capability has been enhanced. The flow rate required to exceed this Venturi meters capabilities (i.e. to create a DP of 5 Bar / 2000"WC and P_2/ P_1 of 0.75) is now 56 MMSCFD or 56 m/s. As with other meter designs, at these surge flow conditions the uncertainty of the flow rate prediction will naturally be somewhat increased, but with a DP transmitter with a URL of 5 Bar in the stack the Venturi meter can cope with surges of 88% in excess of the designed full scale while metering the flow and without failing or sustaining damage.

It is curious that the natural gas industry tends to regard all DP meters as being incapable of dealing with surge flow when the Venturi meter is properly equipped to deal with this adverse event. Note however that orifice meters are not so suitable for surge flow applications due to plate deformation when the DP gets excessive. The cone meter's ability to cope with surge depends on the particular design. If the support bar is strong, and the cone is well gusseted, cone meters should be able to cope with surges in the flow.

3. CALIBRATION OF CONE AND VENTURI METERS

"Quality means doing it right when no one is looking." - Henry Ford

ISO 5167-2 [1] describes the orifice meter performance for a range of orifice meter geometries and gives associated uncertainties with the discharge coefficient predictions. Orifice meters within the geometry and flow condition range of ISO 5167-2 do not generally require calibration.

However, *this is not true of cone and Venturi meters*. Cone and Venturi meters must be calibrated across their applications full Reynolds number range.

There is published evidence that any pair of nominally identical cone meters do not necessarily have identical performances. In 2009 CEESI (Hodges [5]) showed that nominally identical cone meters had different discharge coefficient vs. Reynolds number relationships. Hodges presented a massed data set of 29 cone meter calibrations showing the spread of discharge coefficients (reproduced here as Figure 10). The range of the data set is shown in Figure 10. Hodges et al stated:

"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 {10} 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."

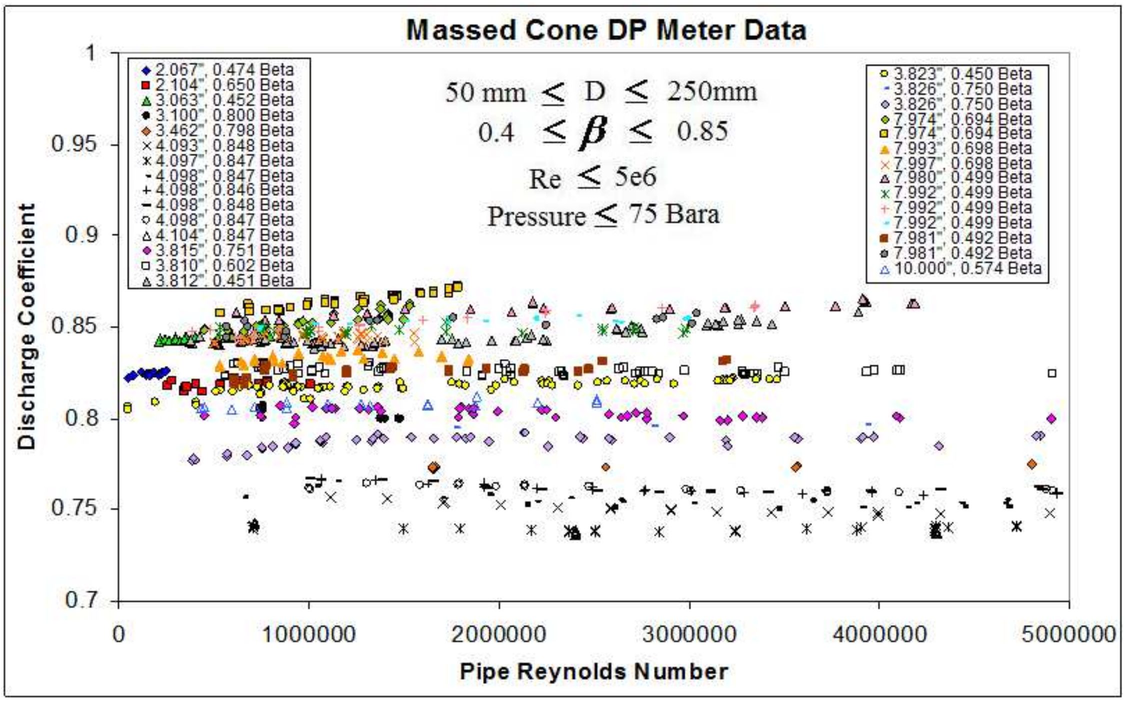

Figure 10. Reproduction of Hodges [5] Massed Cone Meter C_d vs. Re Data Set

ISO 5167-4 is a Venturi meter standard that includes information on machined convergent section Venturi meters, i.e. the common design used in the natural gas production industry. ISO states the limits to the ISO Venturi meter discharge coefficient prediction (C_d=0.995, ±1%) for machined convergent section Venturi meters. They are:

50 mm ≤ D ≤ 250 mm	0.4 ≤ β ≤ 0.75
2e5 ≤ Re (D) ≤ 1e6	Pressure ≤ 10 Bar(a)

ISO states that outside these limits the Venturi meter should be calibrated: "Research into the use of Venturi tubes in high-pressure gas [≥ 1 MPa (≥ 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. For optimum accuracy Venturi tubes for use in gas should be calibrated over the required flow rate range." ISO also states that "For installations outside the limits defined for D, β and Re, it remains necessary to calibrate separately the primary element in its actual conditions of service." Furthermore, ISO also states that "… a simultaneous use of extreme values of D, β and Re shall be avoided as otherwise the uncertainties given are likely to increase."

Re (d)	Cd	Uncertainty (%)
1e6 to 2e6	1.000	2
2e6 to 1e8	1.010	3

Table 2. ISO 5167 Annex B Machined Convergent Section Venturi Meter C_d Estimates.

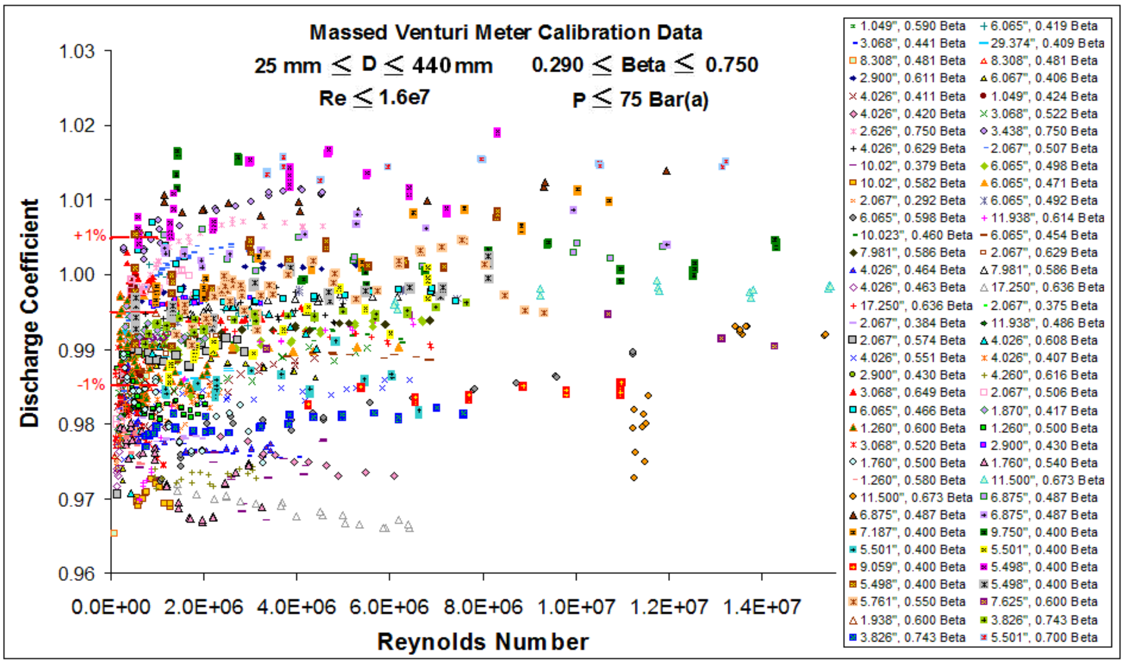

Figure 11. Massed Venturi Meter C_d vs. Re Data Set Data Set

Industry uses Venturi meters outside these limits. ISO 5167-4 states regarding extrapolation "…the number of tests available on this subject is small and these tests were mostly carried out on Venturi tubes, whose geometry was not strictly in accordance with ISO 5167-4. As a result the reliability not only of the discharge coefficient but also of the uncertainties is relatively low". ISO also states: "When Re(D) increases above 1e6 the pattern of C_d vs. Re(D) is not very predictable. Sometimes there is a slight increase in C_d with Re(D): sometimes there is a substantial but gradual increase; sometimes there is a substantial and sudden increase." ISO gives further discharge coefficient estimates in Annex B (that is "*informative"* only) using *throat diameter* Reynolds numbers, Re(d). The relationship between throat and pipe Reynolds number is: Re(D)=β*Re(d). The ISO Venturi meter beta ratio range is 0.40 ≤ β ≤ 0.75. The effective throat diameter range that corresponds to Re(D)>1e6 is Re(d)>1.33e6. Table 2 reproduces ISO's predictions for machined convergent section Venturi meters at 1e6 ≤Re(d) ≤1e8.

CEESI gathered a massed data set of 71 machined convergent ISO compliant geometry Venturi meters. No data set is a repeat calibration of the same meter. Although much of the data is from CEESI there are several data sets from 3rd party calibration facilities. There are six different identified manufacturers. The range of the data (except one 750mm meter data set) is:

25 mm ≤ D ≤ 440 mm	0.29 ≤ β ≤ 0.75
Re (D) ≤ 1.6e7	Pressure (Bara) ≤ 75 Bara

Figure 11 shows the massed data set. ISO's comment regarding the pattern of C_d vs. Re (D) not being very predictable at Re(D) >1e6 is borne out. Here then is evidence that any pair of nominally identical Venturi meters do not necessarily have identical performances. Superimposed on the graph is the ISO prediction of C_d=0.995 and stated uncertainty of 1%. This ISO prediction is not applicable to this data set as most of the data is for Re (D) >1e6 and all data is for pressure >10 Bar. The ISO C_d value is only shown as a comparison and as a warning not to apply it outside the range stated by ISO.

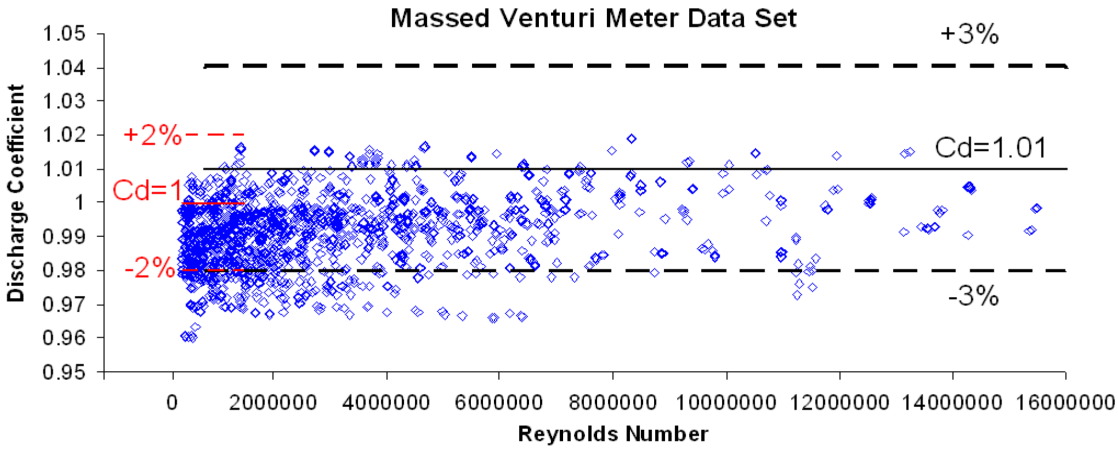

Figure 12. Massed Venturi Meter C_d vs. Re Data with ISO 5167 Annex B C_d vs. Re Prediction.

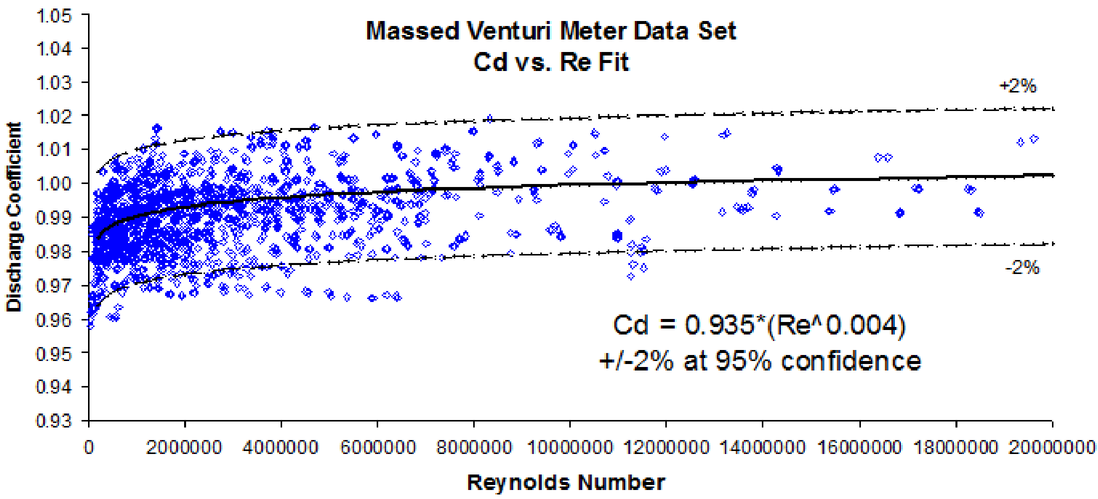

Figure 13. An Example of a Simple C_d vs. Re Fit to the Massed Venturi Meter Data Set.

Figure 12 shows the massed data with the ISO discharge coefficient prediction from the ISO Annex B superimposed on the data. The ISO prediction tends to over-estimate the discharge coefficient and does not fit the data within the uncertainty bands.

$$C_d = 0.935 * \mathrm{Re}^{0.004} \quad \text{-- (11)}$$

Fitting the massed data set to a constant C_d produced C_d = 0.989 ±2.5% at 95% confidence. A simple curve fit of the data produced equation 11 (see Figure 13). This fit has an uncertainty of 2% at 95% confidence. ***CEESI does not claim that this fit is the best data fit to this data***. It is an *example* of a fit to show the general spread of the data. It is evident that across the geometry range of Venturi meters tested the discharge coefficient cannot be predicted without individual calibration to an uncertainty less than 2%. As most natural gas flow metering applications require a better performance than 2% uncertainty it is necessary to calibrate Venturi meters. However, it should be noted that after *proper* calibration (i.e. flow testing across the applications full Reynolds number) the Venturi meter C_d vs. Re data fit can be expected to predict the C_d to 0.5% uncertainty. These results develop the work of Geach et al [6] who in 2005 showed similar results with 18 Venturi meter data sets (for 6"≤ D ≤10" and 0.48 ≤ β ≤ 0.70). This new massed data set validates the comments made by Geach based on the limited data set available at the time.

4. COMMENTS ON DP METER SIZING PROCEDURES

"*There's no sense in being precise when you don't even know what you're talking about.*"
- John von Neumann

When a DP meter is "sized" (i.e. the beta ratio is calculated) for a given application certain assumptions have to be made. The operator supplies the applications *estimated* flow conditions and typically states a maximum permissible DP. The manufacturer then *estimates* the future meters discharge coefficient and uses this approximate information to calculate the appropriate beta ratio. However, **it is pointless to calculate a <u>precise</u> beta ratio with <u>estimated</u> inputs.**

Say an 8", sch 120 (i.e. 0.1826 m) Venturi meter is required for a natural gas flow. The DP is not to exceed 400"WC (i.e. approximately 1 Bar). The flow condition *estimates* are shown in Table 3. Say, the flow rate is expected to be 2000 m^3/hr, i.e. 21.3 kg/s (i.e. 88 MMSCFD).

Pressure (Bar)	Temperature (K)	Molecular Weight	Density (kg/m^3)	Isentropic component
50	300	17.5	38.3	1.3

Table 3. Reservoir Engineer Estimates

To calculate the appropriate beta ratio for a Venturi meter *two assumptions* are required. The first is that the future meters discharge coefficient is some precisely known value. The second is that these conditions are the true maximum flow conditions the meter will encounter. However, as described in Section 3, before manufacture and calibration it is not realistic to assume you can predict *precisely* the Venturi meter discharge coefficient. Furthermore, it is unlikely that the actual flow conditions will be *precisely* the stated reservoir engineer predictions. However, in order to choose a beta ratio at the design stage, the engineer is impelled to *assume* a discharge coefficient and that the estimated flow conditions are correct. Let us say that the engineer makes the assumption C_d = 0.989 (i.e. see section 3). With the estimated maximum flow rate and flow conditions equation 2c now has only one unknown, the beta ratio which can be found by iteration. (Note $\varepsilon = f(\beta, \kappa, P, \Delta P)$, see foot note 4.)

The beta ratio required for a Venturi meter to produce 400"WC ***if*** the discharge coefficient is *precisely* 0.989 and ***if*** the reservoir engineering estimates are *precisely* correct is 0.5374. The inlet diameter is fixed at 7.187" (0.1826m) so the throat diameter is manufactured to 3.863". The Venturi meter is *then* calibrated to find the actual discharge coefficient and regardless of the result then sent out as fit for service. However, this calibration is required because the initial discharge coefficient estimate is not precise, e.g. in section 2 we saw that C_d = 0.989 ± 2.5%, i.e. 0.964 ≤ C_d ≤ 1.014. Therefore, although the Venturi meter was sized to produce 400"WC at the maximum flow condition with C_d = 0.989, at these flow conditions the Venturi meter will actually produce a maximum DP within the range 380"WC ≤ ΔP ≤ 422"WC, i.e. approximately 400"WC ± 20"WC, i.e. approximately 400"WC ±5%. Hence, the actual meter may or may not produce a DP < 400"WC due to the discharge coefficient uncertainty. The actual flow conditions are *usually* (but not always!) close to, but not precisely the same as, the conditions predicted and used to size the meter. The actual flow conditions can induce either larger or smaller DP's than predicted. For example, let us say that the real application produces flow conditions shown in Table 3a.

Pressure (Bar)	Temperature (K)	Molecular Weight	Density (kg/m^3)	Isentropic component
50.3	305	17.7	38.1	1.3

Table 3a. Reservoir Engineer Estimates

Consider the DP's if the actual flow rate was +5% or -5%, i.e. 2100 m^3/hr or 1900 m^3/hr of the sizing estimate. If the actual discharge coefficient was indeed 0.989 then the actual DP created by 2100 m^3/hr at these conditions is approximately 440"WC and the actual DP created by 1900 m^3/hr at these conditions is approximately 360"WC. Hence, the actual meter may or may not produce a DP > 400"WC due to the differences between the actual and predicted flow conditions.

In reality these two DP influencing factors co-exist. They can both cause increases or decrease the actual DP, or they can influence the DP in different directions. Regardless, these effects are not predictable when the meter is being sized. Therefore, there is a 50/50 chance that the actual DP's will be larger than predicted. If the meter is sized to a maximum allowable DP, then **<u>if no precautionary measures are taken</u>** there is a 50/50 chance that the actual DP will exceed the allowed maximum DP. This could lead to a saturated DP transmitter and a mis-measurement. In the above example the limit of the problem is a discharge coefficient of 0.964 and the actual conditions with 2100 m^3/hr producing 464"WC. This then is substantially different to the desired maximum of 400"WC. Therefore, it is important that precautionary measures are taken. However, there is little to no formal information in the literature regards what these measures should be.

One precaution is to size the Venturi meter for a higher flow rate than expected. This significantly reduces the chance of excessive DP values and a saturated DP transmitter while doing little to reduce the ability of the meter. In the above example the meter could be sized for a flow rate 20% greater than the expected maximum, i.e. 2400 m^3/hr. At these stated flow conditions (i.e. Table 3) and C_d = 0.989 the beta ratio required to produce 400"WC at 2400 m^3/hr is 0.5836. If in service at these flow conditions this meter would (for C_d = 0.989) produce 275"WC at 2000 m^3/hr. The potential spread of C_d of $0.964 \leq C_d \leq 1.013$ produces 262"WC ≤ ΔP ≤ 290"WC, i.e. DP < 400"WC. If the actual discharge coefficient was indeed 0.989 but the actual flow conditions were say, those of Table 3a at 2100 m^3/hr or 1900 m^3/hr, then the DP's produced would be 247"WC ≤ ΔP ≤ 303"WC, i.e. DP < 400"WC. In the case of the "perfect storm" with a minimum discharge coefficient of 0.964, the flow conditions of Table 3a and 2100 m^3/hr the DP is still only 320"WC, i.e. DP < 400"WC. Hence, by sizing the Venturi meter for 20% higher flow rate the problem of saturating the DP transmitters is very significantly diminished. With a DP transmitter stack with an URL of 400"WC, even with the original estimated maximum flow of 2000 m^3/hr producing no more than 275"WC, there is still the potential for a DP turndown of 275"WC:2"WC, i.e. 137.5:1 which is a flow rate turndown of √137.5:1, i.e.11.7:1. If the meter had been sized to attempt create the maximum stated allowable DP for this application of 400"WC the aimed for DP turndown would have been 400"WC:2"WC, i.e. 200:1, i.e. a flow rate turndown of √200:1 or 14.1:1 (see Table 1). Therefore, from equation 1, the meter sized to avoid accidental DP transmitter saturation with a turndown of 11.7 (i.e. y=11.7) still covers > 98% of the flow range of the meter set to a nominal maximum DP of 400"WC with a turndown of 14.1 (i.e. x=14.1). Furthermore, by sizing the meter to 20% higher flow rate the meter inherently has some surge capability (which is enhanced by stacking a higher range DP transmitter than normal flow will require- see section 2c.)

The current practice of one North Sea operator for avoiding DP transmitter saturation was described to the authors. During commissioning technicians monitor the DP. "If the DP transmitter saturates then we go to the store and get another one with a higher range!" Whereas this is a solution, there are two inherent shortcomings in this approach. The first issue is that the maximum DP the meter will encounter in service is not always guaranteed to be produced during the commissioning of the meter. Larger DP's may be produced and DP transmitters saturated only after commissioning is complete[7]. The second issue is that the operators typically request a maximum DP. The manufacturers are obliged to make reasonable effort to assure the DP will not

[7] During wet gas flow DP meter testing at CEESI where the client has chosen the DP transmitter range and is logging their own data it is common for the DP transmitters to become saturated. It is almost as common for the client to not to notice and to query CEESI why their data looks incorrect. If engineers deliberately subjecting the meter to adverse conditions do not always notice DP transmitter saturation, how likely is it that the issue would be noticed in a service meter where no problem is expected?

exceed the client's desired maximum value. An operator policy of simply using a higher DP range undermines the whole concept of asking for a maximum DP in the first place. Of course, by the commissioning point in the proceedings the operator will almost always go with what he has got and resize the DP transmitter. However, this is hardly a good alternative to sizing the meter appropriately from the outset to insure the meter meets its specification.

Saturation of DP transmitters due to sizing uncertainties is a genuine issue regards DP meter integrity. One solution is to size the meter to some higher flow rate than expected. This practice does occur in industry but curiously there is little in the literature formalizing such a methodology. Operators do sometimes utilize this practice, although often with surge capability in mind rather than any conscious effort to mitigate DP saturation concerns. Manufacturers are less likely to automatically utilize such a practice. Without agreement from the client it could be perceived by the client that the manufacturer has been negligent by sizing the meter to a wrong maximum flow rate. Furthermore, all manufacturers naturally wish to produce on paper the best possible turndown. Using the above example, they would rather say the meter has a turndown of 14.1 rather than 11.7:1. It sounds better, and unfortunately the majority of operator and manufacturer engineers (regardless of what individuals would claim if put on the spot!) do not understand that the flow range difference between these two turndowns is practically trivial, i.e. < 2%. It is the operator's prerogative to tell the manufacturer to size the meter to some higher flow rate.

If a DP meter's discharge coefficient is not *precisely* known at the design stage (as is the case for Venturi and cone meters) **there is no point designing the meter to a precise beta ratio to four decimal places!** Continuing with the above Venturi meter example, we have C_d = 0.989 ± 2.5%. For the conditions in Table 3 at 2000 m^3/hr the required beta ratio to actually achieve 400"WC lies somewhere within the range β =0.5374 ±1.1%, i.e. 0.5315 ≤ β ≤ 0.5433. Furthermore, as described above the actual flow conditions are likely to be slightly different than the predicted flow conditions. Table 4 shows examples of what beta ratio is actually required to produce the desired 400"WC under various realistic scenarios of the actual discharge coefficient and flow conditions varying around a reasonable range.

Table 4 shows that although the Venturi meter would be sized to β = 0.5374 for this application in reality to produce the desired maximum 400"WC a different beta ratio could be required. In this example the beta ratio required to produce 400"W is: β = 0.5374 ± 3.5%, i.e. 0.5184 ≤ β ≤ 0.5553. **It should therefore be self-evident that there is no point in sizing a DP meter to a beta ratio of four decimal places.** A DP meter beta ratio sized to four decimal places is not just pointless, it actively produces a false sense of precision. The true precision of a DP meter is based on the discharge coefficients calibration uncertainty and the integrity of the associated instruments.

Cd	Beta Ratio Table 3 Conditions 2000 m3/hr	Beta Ratio Table 3a Conditions 2000 m3/hr	Beta Ratio Table 3a Conditions 2100 m3/hr	Beta Ratio Table 3a Conditions 1900 m3/hr
0.964	0.5438	0.5431	0.5553	0.5305
0.989	0.5374	0.5368	0.5489	0.5242
1.013	0.5315	0.5309	0.5429	0.5184

Table 4. Examples of Beta Ratio Requirement Variation with Varying C_d and Flow Conditions.

It is suggested here that DP meters should not only be sized to cope with a higher flow rate than the maximum flow rate predicted (with the chosen over-range being case dependent on engineering judgment) but that the beta ratio selected should only have **two** decimal places. Any more decimal places are practically meaningless while the precise discharge coefficient is not known and falsely imply more precision than actually exists.

Continuing the example, the Venturi meter originally sized to β=0.5374 for the conditions in Table 3 and 2000 m3/hr was re-sized above to β=0.5836 to assure DP<400"WC. More precisely, the meter could be sized to only two decimal places by rounding *up* (to continue the theme of reducing the maximum DP) to β =0.59. At the nominal flow conditions of Table 3 and 2000 m3/hr a discharge coefficient of C_d = 0.989 & beta ratio of β = 0.59 produces a DP of 262"WC (instead of a β = 0.5836 DP of 275"WC). The DP turndown with the nominal maximum flow conditions shown in Table 3 and 2000 m3/hr is 262"WC":2"WC, i.e. 131:1 which is a flow rate turn down of √131:1, i.e. 11.4:1. Equation 1 indicates that this still covers > 98% of the range of a meter sized to a nominal maximum of 400"WC with its ideal flow rate turndown of 14.1. That is, rounding up the calculated beta ratio to two decimal places removes the perception of false precision while producing no significant practical disadvantage. Such a DP meter is sized such that:

- the selected beta ratio value avoids suggesting false precision,
- the maximum requested DP will not be exceeded with flow conditions that even loosely resemble the flow condition predictions regardless of the calibrated discharge coefficient,
- the flow range difference between this beta ratio choice and that of the "ideal" beta ratio for the nominal flow conditions is practically negligible,
- the meter has significant surge capacity.

This example has been conducted arbitrarily for Venturi meters. The same issues exist for all DP meter designs that require calibration (e.g. cone, wedge etc.) and / or may be applied in different flow conditions than those initially predicted. As a calibration facility CEESI tests many Venturi and cone meters annually. It is common for the actual discharge coefficient to be lower than predicted during the manufacturers sizing and the DP's produced to be higher than predicted. Whereas, CEESI (and no doubt other calibration laboratories) are diligent with measurement of these DP's, no operator or manufacturer ever seems to note this as a potential issue or request to be notified of this issue. Perhaps, in some cases the operator and manufacturer discuss this in private. However, the authors rather suspect not. In most cases the issue likely goes unnoticed. As such it seems sensible to size the meter mandatory as described above in order to engineer out the problem so that the technicians seldom have to encounter it.

Finally, note that this discussion on the beta ratio being set to two decimal places only refers to the sizing procedure. Once the meter is subsequently manufactured it is still good practice to measure and report the actual manufactured meter geometry to a high degree of accuracy.

5) COMPARISONS OF DP METER SIGNAL STABILITY

"It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so." Mark Twain

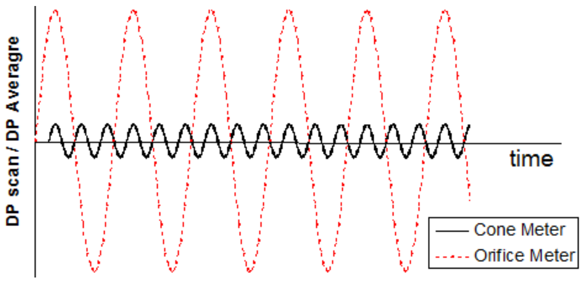

Fig 14. Cone Manufacturer Suggested DP Deviations.

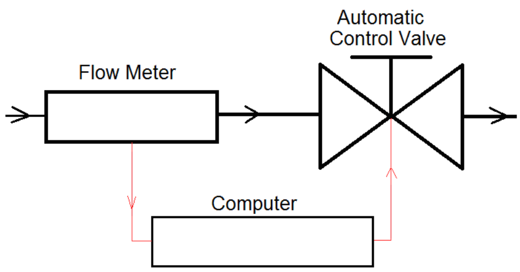

Fig 15. Control System.

It is claimed in manufacturer literature that for a given application a cone meter's DP has a lower standard deviation than an orifice meter's DP. That is, the cone meter is promoted as having a more stable DP signal than the orifice meter. Figure 14 graphically represents this claim. This claim is important for two reasons. First, it is claimed that a more stable DP allows lower DP's to be read thereby allowing larger flow rate turndowns. Second, the more stable the DP the shorter the time required to register a flow rate change and the more attractive that meter design becomes to designers of control systems (such as feed-forward or feed-back control valve systems, see Figure 15). The authors could find no independent data on DP meter signal stability and therefore investigated the issue.

The CEESI wet gas flow facility can operate with several flow meters in series. As wet gas tests are usually preceded by dry gas flow tests CEESI has multiple data sets of several DP meters in series at the same gas flow conditions. In several cases orifice, cone and Venturi meters have been tested in series. CEESI can compare the three DP meters DP fluctuations for given flow conditions. Rosemount 3051 DP transmitters were used to measure the DP's. These transmitters can read DP's up to 7Hz. However, up until 2011 the scan rate of the data acquisition system was 6 seconds, meaning that each DP meter had a snap shot of the DP read every six seconds. A test would last typically a minimum of 5 minutes meaning that a minimum of 50 DP samples were taken, averaged and standard deviation checked before a data point was accepted. This point to point data for the orifice, cone and Venturi meter data can be compared to check relative stability.


Fig 16. 4",sch 40, 0.62β orifice


Fig 17. 4",sch 80 0.6β Venturi


Fig 18. 4",sch 80 0.75β cone

Figures 16 thru 18 show a 4", 0.62β orifice meter, a 4", 0.60β Venturi meter and a 4", 0.75β cone meter respectively installed in series in that order. The unobstructed straight pipe length upstream of each meter is >50D. Figure 19 shows the three meters DP fluctuations for a randomly selected flow condition of 200psia and 72 ft/s. The cone meters DP was found to have a larger fluctuation relative to its magnitude than the orifice and Venturi meters, which seem to have similar fluctuations of DP relative to their DP magnitudes. This was not the result expected. It was suspected that this may be an abnormal result for some unknown reason and other flow conditions were therefore looked at. All flow conditions gave the same result. Figure 20 shows the results from the same test configuration when the flow was at 650 psia and 50 ft/s.

This unexpected result lead to a review of possible causes. It was suggested that perhaps the cone meters location in the re-circulating facility was poor due to upstream disturbances or due to some local system resonance. However, with each meter having >50D of straight upstream pipe flow disturbance was unlikely. Furthermore, during operation of the facility CEESI has always been very conscientious about the control and mitigation of any vibration issues. No vibration was evident during these tests. CEESI found another set of test results where these DP meters where in series but in a different sequence. The installation order was orifice, cone and then Venturi meter. The 4" orifice meter fitting had a different plate with a 0.68 beta ratio. Figure 21 shows a representative sample of all the dry gas flow results, this sample having flow conditions of 553 psia and 77 ft/s. Again, the cone meters DP fluctuation was significantly greater than the orifice and Venturi meter. All other dry gas flow conditions showed similar results.

In these tests the cone meter had a larger beta ratio than the other DP meters. It was therefore suggested that the standard deviation of a DP meter may be beta ratio dependent. CEESI looked for different cone meter beta ratio data. This was scarce, but one test was found where a 4", 0.66 beta ratio Venturi meter (not shown) was installed upstream of a 4", 0.63 beta ratio cone meter (Figure 22). The earlier evidence suggests orifice and Venturi meters have similar DP fluctuations. Figure 26 shows the DP fluctuation comparison at a random flow condition. All the dry gas flow conditions gave similar results. Again, even with similar beta ratios the cone meters DP fluctuation was significantly higher than the Venturi meter.

In 2011 CEESI commissioned an 8" wet gas flow facility. An 8", 0.75 beta ratio cone meter (Figure 23) was installed upstream of an 8", 0.6 beta ratio Venturi meter (Figure 24) which in turn was upstream of a 8", 0.69 beta ratio orifice meter (Figure 25). Again, the meters were separated

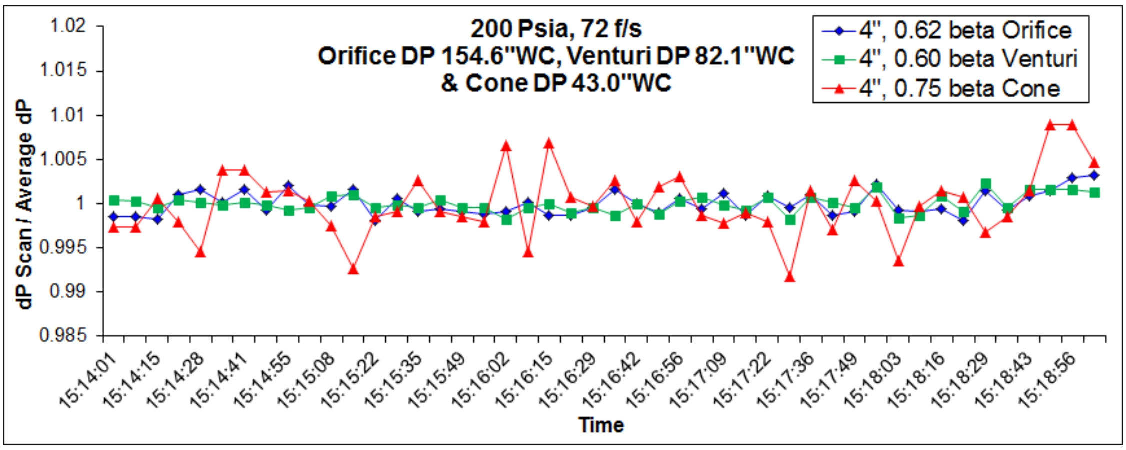

Figure 19. DP fluctuations of an Orifice, Venturi and Cone Meter in Series at 200 psia & 72ft/s.

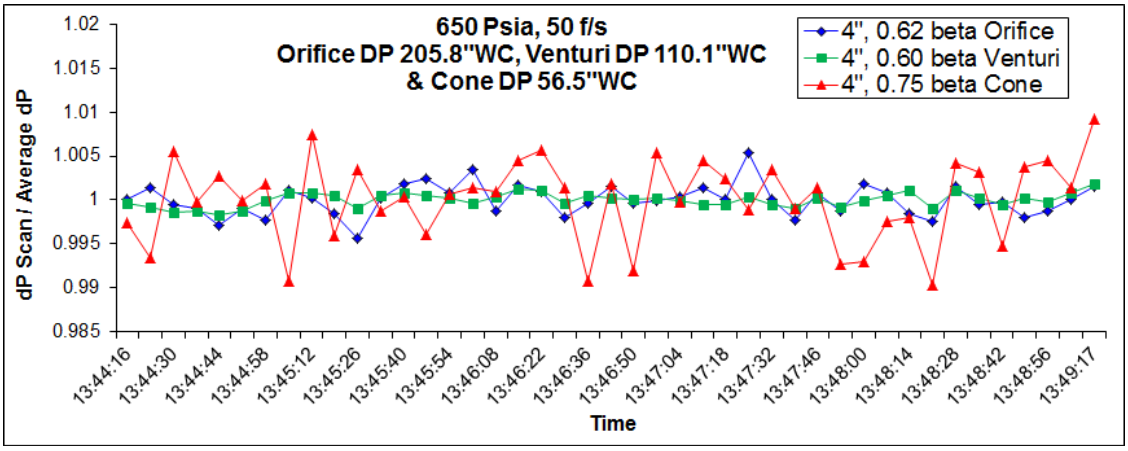

Figure 20. DP fluctuations of an Orifice, Venturi and Cone Meter in Series at 650 psia & 50 ft/s.

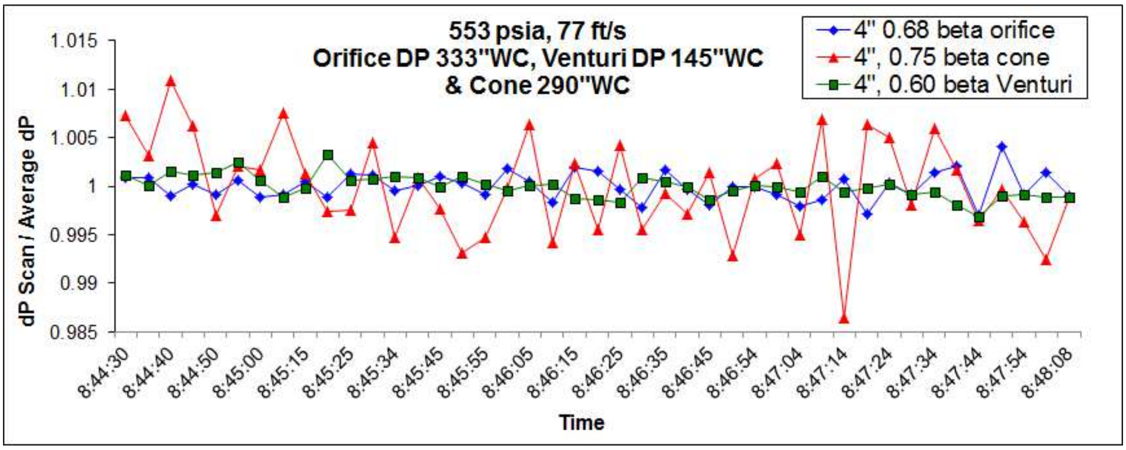

Figure 21. DP fluctuations of an Orifice, Cone and Venturi Meter in Series at 553 psia & 77 ft/s.

by more than 50D and Rosemount 3051 DP transmitters were used. The new CEESI wet gas facility data acquisition system scan took 1 second and five minute tests were run. Figure 27 represents the three DP meters DP standard deviation values at the eight dry gas flow conditions tested. The flow conditions were natural gas flow at 1) 217 psia, 40ft/s, 2) 208 psia, 43 ft/s, 3) 216 psia, 45 ft/s, 4) 209 psia, 50 ft/s, 5) 637 psia, 40 ft/s, 6) 1024 psia, 37 ft/s, 7) 645 psia, 56 ft/s & 8) 1024 psia, 50 ft/s. Clearly, the cone meters DP standard deviations are again significantly higher than for the orifice and Venturi meters.

Fig 22. 4”,sch 80, 0.63 β cone meter.

Fig 23. 8”,sch 80, 0.75 β cone meter.

Fig 24. 8”,sch 80, 0.60 β Venturi meter.

Fig 25. 8”,sch 40, 0.69 β orifice meter.

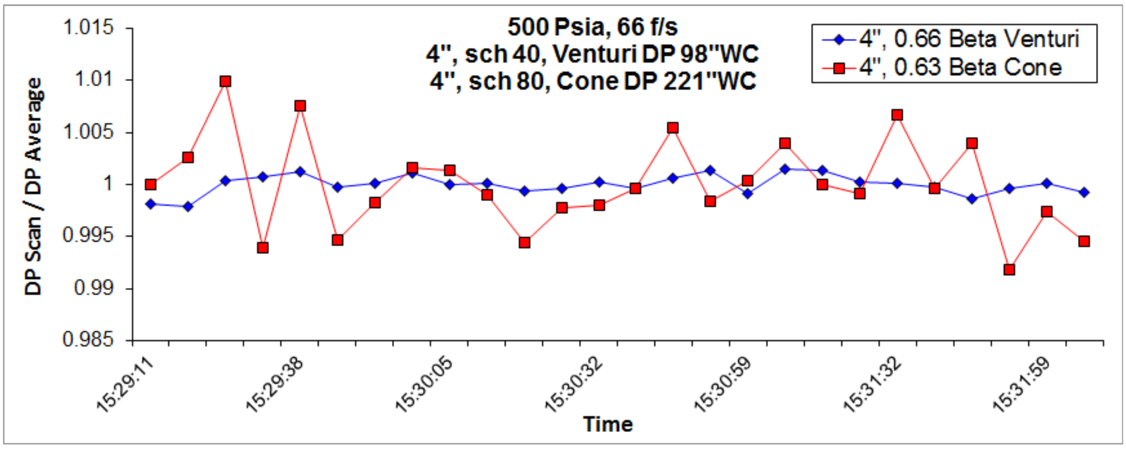

Figure 26. DP fluctuations of a Cone and Venturi Meter in Series at 500 psia & 66 ft/s.

It was then suggested that perhaps the cone meter is somehow more sensitive than other DP meters to any pulsation caused by a re-circulating facility with compressors. It was also postulated that perhaps a different type of DP transmitter should be used to discount any unspecified DP transmitter effect. CEESI therefore reviewed test data from an air blow down test facility. This facility has no inherent pulsation and used Honeywell DP transmitters, i.e. a different transmitter design to the CEESI wet gas flow facility. The Honeywell DP transmitters can scan at 3Hz. However, the scan rate at the air blow down calibration facility is 2 Hz. The flow is held steady for 10 seconds meaning 20 sample DP’s are read and averaged. The standard deviation is noted to assure stability. If there were any pulsation or DP transmitter effects on the cone meter at the re-circulation natural gas facility it would be alleviated in the air blow down facility.

CEESI found a 4”, 0.63 beta ratio cone meter (Figure 28) data set and a 4”, 0.60 beta ratio paddle plate orifice meter (Figure 29) data set both tested at separate times by coincidence at similar

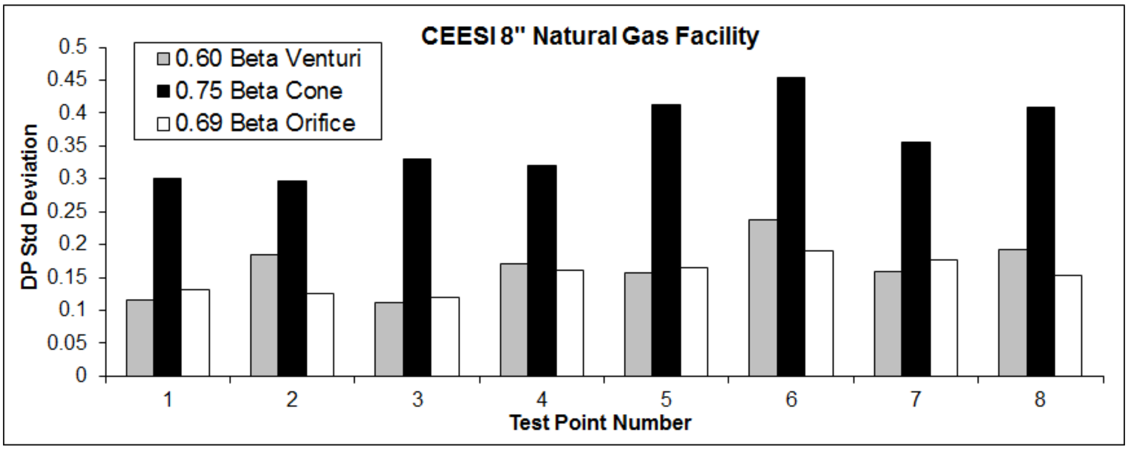

Fig 27. DP Standard Deviations of a Venturi, Cone & Orifice Meters at Various Flow Conditions.

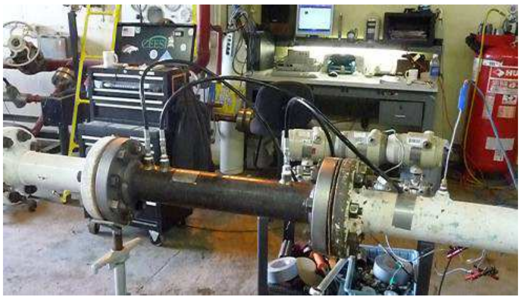

Fig 28. 4",sch 80, 0.63 β cone meter.

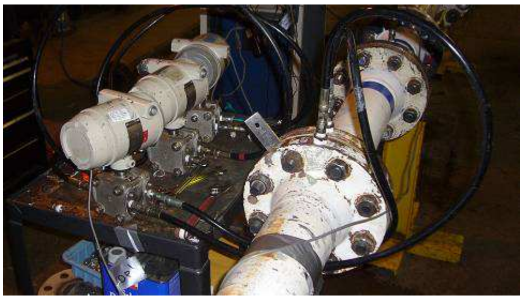

Fig 29. 4", 0.60β paddle plate orifice meter.

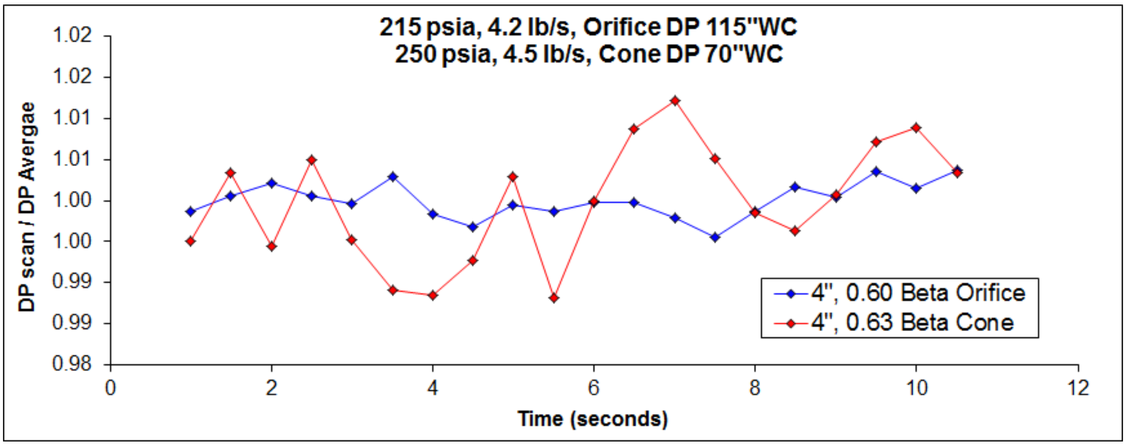

Fig 30. DP fluctuations of Orifice & Cone Meters in an Air Blow Down Facility at 4.3 lb/s.

flow conditions. Figures 30 shows a representative result. Again all the different flow condition data agreed. The cone meters DP standard deviation is significantly more than an orifice meter in similar flow conditions. Hence, the cone meters larger DP standard deviation is not caused by any pulsation or DP transmitter effects. It appears to be a characteristic of the meter design.

This research strongly suggests that rather than the cone meter having a lower DP standard deviation than an orifice meter (as is often suggested) the very opposite is true. Orifice and Venturi meters have a lower standard deviation than a cone meter. Therefore, a cone meter does not have a turndown advantage due to any DP stability benefits (hence this topics absence from the discussion in section 1). A cone meter does not appear to have a fast response time than other DP meters. However, it should be remembered that as long as a DP meters signal can be averaged to a repeatable value for a constant flow rate, the size of the DP standard deviation is not greatly important for anything other than the specialist case of fast response control systems. Therefore, differing DP standard deviation between competing DP meter designs is of little practical consequence. Furthermore, the cone meter has other advantages, not least its *exceptional* resistance to significant flow disturbances (e.g. Hodges [5]).

6 DP METER RESPONSE TO WET GAS FLOW – NEW DATA AND ANALYSIS

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."
John von Neumann

DP meter reaction to wet gas flow has been important for many years. However, industry does not yet have a comprehensive understanding of how wet gas flow affects DP meter performance. Physical understanding (and modeling) of the phenomenon is far from complete. Most DP meter wet gas flow performance statements come in the form of wet gas "correlations". Some correlations are based on some modeling with data fitted parameters required, and most have at least some physical boundary conditions applied. These "semi-empirical" correlations have various levels of sophistication. In general it is beneficial for semi-empirical correlations to have as few free parameters as possible (i.e. to be as *simple* as possible) compared to the size of the data set. The more complex the fit for a fixed size data set the higher the risk of interpolation and extrapolation of the correlation producing errors. However, all semi-empirical correlations carry some interpolation and extrapolation risk, as the "empirical" part of the fit is effectively an admission of lack of knowledge. Hence, new DP meter wet gas flow data out with the range already held by industry is of great interest as it allows industry to check the validity of extrapolating existing correlations, or to develop better wider ranging correlations, while improving the physical understanding of DP meters wet gas flow.

6a. REVIEW OF WET GAS FLOW PARAMETERS

The liquid flow relative to the gas flow is quantified by the Lockhart-Martinelli parameter, X_{LM} (see equation 12). The gas to liquid density ratio, DR, is a non-dimensional description of pressure for set fluid types (see equation 13). The gas densiometric Froude number, Fr_g, is a non-dimensional description of the gas flow velocity for a set pipe size and fluid properties (see equation 14). The Water Liquid Mass Ratio, WLR_m, is the ratio of the liquid phase's water to total mass flow rate (see equation 15). The "Over-Reading" percent, OR%, is defined as the bias (i.e. error) induced on the gas flow meter by the presence of the liquid (see equation 16). Note that m_g & m_l are the gas and liquid mass flow rates respectively, m_w & m_{hcl} are the water and hydrocarbon liquid mass flow rates respectively, $m_{g,apparent}$ is the uncorrected gas flow rate prediction of the meter, ρ_g & ρ_l are the gas and liquid densities respectively and g is the gravitational constant.

$$X_{LM} = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_\ell}} \text{ -- (12)}, \qquad DR = \rho_g / \rho_l \text{ -- (13)}, \qquad Fr_g = \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \text{ -- (14)}$$

$$WLR_m = \frac{\dot{m}_w}{\dot{m}_w + \dot{m}_{hcl}} \text{ -- (15)} \qquad OR\% = \left(\frac{\dot{m}_{g,apparent}}{\dot{m}_g} - 1\right) * 100\% \text{ -- (16)}$$

6b. 8", 0.75 BETA RATIO CONE DP METER WITH WET GAS FLOW RESPONSE

In 2011 CEESI commissioned an 8" multiphase wet gas flow facility. It was commissioned with an 8", sch 80, 0.75 beta cone meter installed (see Figure 23). This cone meter had been previously gas flow calibrated to C_d = 0.821 ±0.5%. It was noted that a major cone meter manufacturers sizing program predicted this meter to have C_d = 0.80, i.e. -2.6% below the calibrated value. This is an example of industry only being able to approximate the cone meter discharge coefficient before calibration and therefore there is no point sizing a cone meter beta ratio to some precise value with more than two decimal places.

Whereas 0.75 beta ratio cone meters between the size 2" to 6" have been relatively well wet gas flow tested this is the first 8", 0.75 beta ratio cone meter data set that the authors are aware of. One of the unknowns regarding DP meter wet gas response is the effect of different meter (pipeline) sizes. There is very little information in the public domain regards how the meter could respond. It is known that pipe size can influence the flow pattern (i.e. the liquid dispersion in the gas flow) and the flow pattern is known to influence a DP meters response to wet gas flow. Therefore, there was no guarantee that this 8" cone meter data would match the latest published wet gas flow correlation for 2" to 6" cone meters with a 0.75 beta ratio. This correlation was released by CEESI in 2009 (see Steven [7]). It is reproduced here as equation set 17 to 19a. The correlation was rated to predict the gas flow rate to ±2.6% to 95% confidence.

$$\dot{m}_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{-- (17)} \qquad C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{-- (18)}$$

where for Frg ≤ 0.5: n = 0.19 -- (19) and for Frg > 0.5 $n = \frac{1}{2}\left(1 - \left(\frac{0.728}{\exp(0.31 * Fr_g)}\right)\right)$ -- (19a).

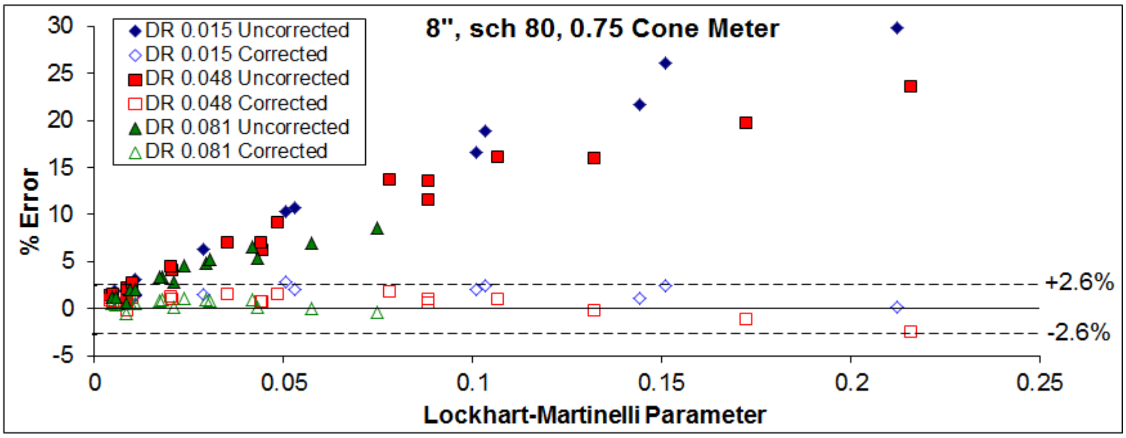

Fig 31. CEESI, 8", 0.75 Beta Ratio Cone Meter Gas / Exxsol D80 Wet Gas Flow Test Results.

During the initial multiphase wet gas flow facilities commissioning the meter was horizontally installed and tested with natural gas and Exxsol D80 (kerosene substitute). The wet gas test range was $X_{LM} \le 0.22$, $0.0148 \le DR \le 0.0814$, $0.96 \le Fr_g \le 3.25$ & $WLR_m = 0$. The results of applying this equation set to the data from this larger 8", 0.75 beta ratio cone meter wet gas tests results are shown by Figure 31. The existing 2" to 6", 0.75 beta ratio cone meter wet gas correlation was found to correctly predict and correct the new 8", 0.75 beta ratio cone meter data set to within the stated uncertainty.

6c ISO TR11583 VENTURI METER WET GAS CORRELATION WITH INDEPENDENT DATA

ISO TC30 has released a Technical Report (TR 11583 [8]) that offers a wet gas correlation for Venturi meters. This correlation is claimed to be applicable over the range given in Table 5. Note that the gas densiometric Froude number stated ($Fr_{gas,th}$) is based on the Venturi meters throat diameter, d. This is related to the standard pipe diameter the gas densiometric Froude number (Fr_g) by equation 21. The ISO TC30 correlation is for gas with light hydrocarbon liquid **or** gas with fresh water. Depending on which liquid is present the correlation switches a free parameter

Inlet Diameter	D ≥ 2”
Lockhart Martinelli Parameter	$0 \le X_{LM} \le 0.3$
Density Ratio	DR > 0.02
Beta Ratio (or Diameter Ratio)	$0.4 \le \beta \le 0.75$
Throat Froude Number, $Fr_{gas,th}$	$Fr_{gas,th} > 3$
Gas Flow Rate Prediction Uncertainty, $X_{LM} \le 0.15$	3%
Gas Flow Rate Prediction Uncertainty, $X_{LM} > 0.15$	2.5%

Table 5. Stated Range of ISO Technical Report [8] Venturi Meter Wet Gas Correlation.

designated as “H”. The correlation does not account for the most common wet natural gas production scenario of the natural gas having a mix of hydrocarbon liquid and water. That is, for WLR_m =0, H=1 and for WLR_m =1, H=1.35, but for the common case of $0<WLR_m<1$ no value of “H” is offered. In fact, natural gas production is technically out with the scope of ISO TR11583 and indeed this is stated in the report’s scope. Furthermore the correlations mathematical structure has proven controversial to some in the natural gas production industry, but these arguments are out with the scope of this paper and were discussed in detail by de Leeuw at el [9] in 2011. However, it is difficult to conceive any other industry finding wet natural gas Venturi metering of more interest than the natural gas production industry. As such, if the correlation was proven to be reliable such academic arguments are likely to hold little weight and the correlation would likely be adopted by the hydrocarbon production industry. Hence, as the ISO TR11583 was published with little independent analysis it is important to take every opportunity to review the performance of this correlation whenever new wet gas Venturi meter data becomes available. The ISO TR11583 wet gas Venturi meter correlation is reproduced here as the equation set 18, 20, 21, 22 & 23.

$$\dot{m}_g = \frac{EA_t Y_{tp} C_d^* \sqrt{2\rho_g \Delta P_{tp}}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{-- (20)} \qquad C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{-- (18)} \qquad Fr_g = \beta^{2.5} Fr_{gas,th} \quad \text{-- (21)}$$

$$C_d^* = 1 - \left(\left\{0.0463 * \exp\left[-0.05 * Fr_{gas,th}\right] * \left(\min\left(\sqrt{\frac{X_{LM}}{0.016}}\right)\right)\right\}\right) \quad \text{-- (22)}$$

$$n = \max\left(\left\{\ 0.583 - \left(0.18\beta^2\right) - (0.578^{-0.8*\left(Fr_g / H\right)}\right)\right\},\ 0.392 - 0.18\beta^2\right) \quad \text{-- (23)}$$

In 2011 CEESI donated three multiphase wet gas flow ISO 5167 compliant Venturi meter data sets to the de Leeuw [9] paper. The three CEESI data sets released in 2011 [9] were for $0 \le WLR_m \le 1$, and hence with no guidance from TR11583 both H=1 & H=1.35 were tried in the correction. The results are reproduced in Figure 32. Two of the three Venturi meters had significant gas flow rate prediction errors in excess of the correlations stated uncertainties. In this paper five new independent wet gas Venturi meter data sets (for WLR_m = 0) have also been corrected using the ISO TR11583 wet gas correlation. Figure 32 also shows new two-phase data sets from five ISO 5167 compliant Venturi meters checked against TR11583’s wet gas correlation. Four of the meters were tested at CEESI. One meter was tested at TUVNEL. The CEESI data is confirmed as independent to the TR11583 data set. It is not known if the NELTUV data set was used in the TR11583 wet gas correlation data fit. Table 6 summarizes the results. Three of the five Venturi meters had a wet gas response as predicted within the uncertainty bands of ISO TR11583. However, two 4”, 0.74β Venturi meters did not have a wet gas response as described by ISO TR11583. These meters were initially dry gas calibrated and then wet gas flow tested in series. The two 4”, 0.74β meters were visually identical and built to the same drawing by the same manufacturer. However, the first meter had a calibrated C_d of 0.994 while the second meter has a calibrated C_d of 0.980, i.e. a difference of -1.4%. Figures 11 in Section 3 show that this is a common result. Each meter was operated in wet gas flow with its appropriate discharge coefficient to produce the OR%. The two meters wet gas responses were similar (although not identical). The ISO correlation over-predicted the wet gas over-reading causing an

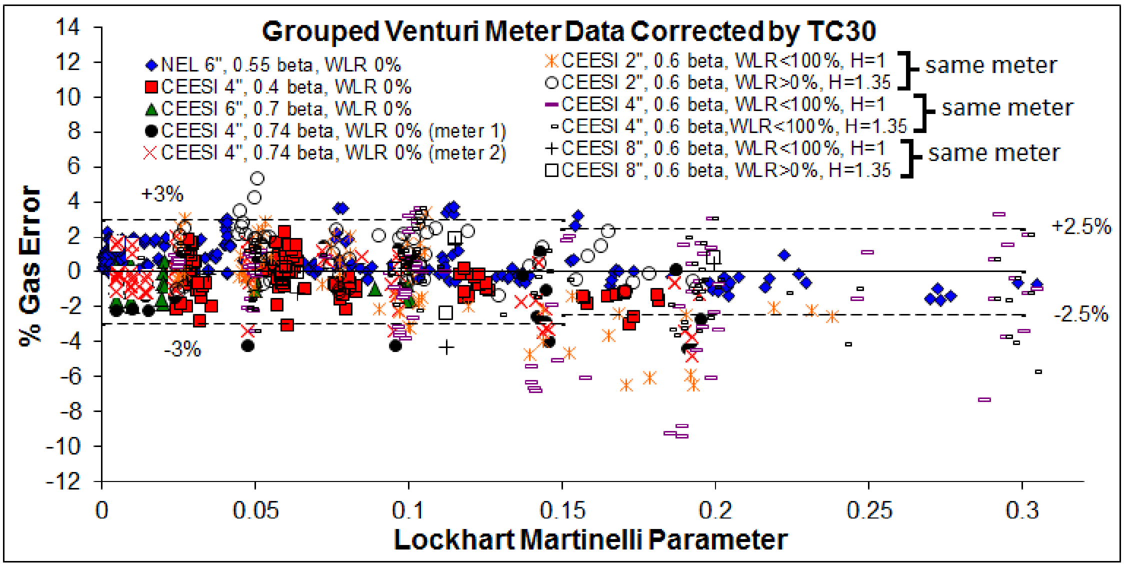

Fig 32. Comparing ISO TR11583 Wet Gas Correlation to Independent Venturi Meter Data.

Meter	WLR Range	No. of Test Points	No. of Outlying Points	Confidence Level	Within ISO Spec?
NEL 6", 0.55β	WLRm = 0	243	6	96%	yes
CEESI 4", 0.40 β	WLRm = 0	124	3	98%	yes
CEESI 6", 0.70 β	WLRm = 0	30	0	100%	yes
CEESI 4", 0.74 β(1)	WLRm = 0	64	8	87.5%	no
CEESI 4", 0.74 β(2)	WLRm = 0	64	8	87.5%	no
CEESI 2", 0.60 β	0≤WLRm≤1	64	For H=1: 13	79.7%	no
			For H=1.35: 5	92.2%	no
CEESI 4", 0.60 β	0≤WLRm≤1	90	For H=1: 26	71.1%	no
			For H=1.35: 15	83.3%	no
CEESI 8", 0.60 β	0≤WLRm≤1	9	For H=1: 0	100%	yes
			For H=1.35: 0	100%	yes

Table 6. Independent Wet Gas Venturi Meter Data Sets Corrected by ISO TR 11583 Correlation.

over correction and a negative bias on the gas flow prediction. Therefore, these independent data sets show that the ISO TR11583 correlation does not correctly predict the two-phase (gas and hydrocarbon liquid) wet gas flow response of all ISO compliant Venturi meters.

Figure 32 and Table 6 also repeat the de Leeuw [9] data for multiphase wet gas flow. It is clear that the ISO TR11583 is not suited for use in multiphase wet gas flow, i.e. within the region 0≤WLRm≤1. At the current time, if an operator wishes to be assured of a low uncertainty wet gas correlation for a Venturi meter it is beneficial to wet gas flow test and data fit each individual meter.

6d. <u>8", 0.690 Beta Ratio Orifice Meter Wet Gas Flow Response</u>

Inlet Diameter	2" ≤ D ≤ 4"
Lockhart Martinelli Parameter	$0 \le X_{LM} \le 0.3$
Density Ratio	0.006 ≤ DR ≤ 0.110
Beta Ratio (or Diameter Ratio)	0.24 ≤ β ≤ 0.73
Gas Densiometric Froude Number, Fr_g	$0.22 \le Fr_g \le 7.25$
WLRm	0%
Gas Flow Rate Prediction Uncertainty	2%

Table 7. Stated Range of Orifice Meter Venturi Meter Wet Gas Correlation.

In 2011 Steven et al [10] discussed the known response of orifice meters to wet gas flow. The massed CEESI & NEL data set of 1656 wet gas flow points for 2", 3" & 4" orifice meters was corrected to > 95% confidence by equation set 17, 18, 24, 25, 26, 27a & 27b. This correlation was applicable for the flow conditions shown in Table 7.

In 2011 CEESI gathered new 8", 0.69β orifice meter data in two-phase (gas / Exxsol D80) flow. Figure 33 shows the uncorrected data and the data corrected with the existing correlation for smaller meters. The existing orifice meter correlation for smaller meters does not fit the data within the correlations uncertainty statement. The correlation underestimates the 8" orifice meters OR% therefore producing a positive bias in the "corrected" data. The data is still corrected to within 4% to 95% confidence, and clearly the correction is significantly better than applying no correction. However, the existing correlation for < 4" orifice meters does produce a small bias when used on the 8" orifice meter. The wet gas flow response of larger DP meters still is therefore an open question.

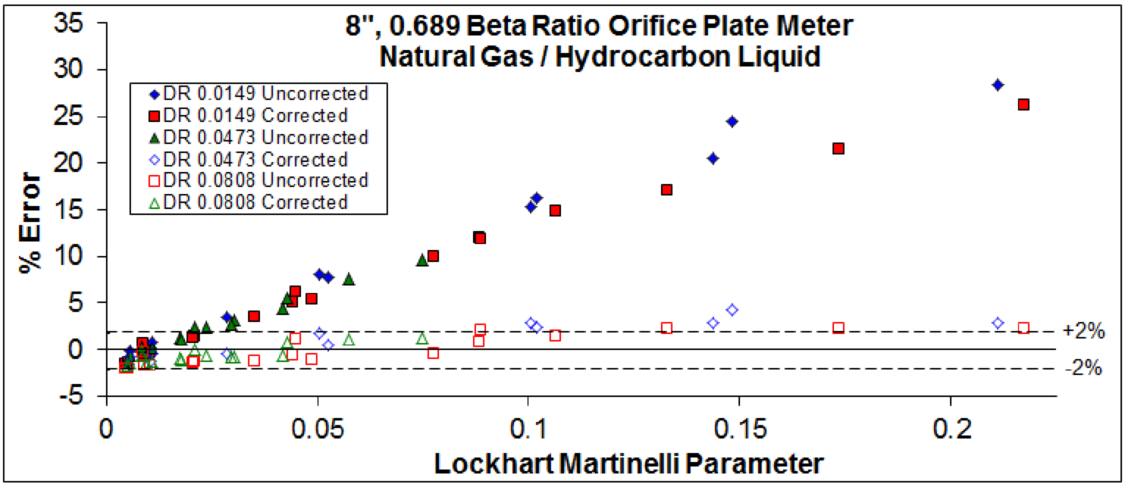

Fig 33. 8", 0.69β Orifice Meter Wet Gas Response & Effect of Applying Published 4" Correlation.

$$\dot{m}_g = \frac{\dot{m}_{g,apparent}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \quad \text{-- (17)} \qquad C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \quad \text{-- (18)}$$

$$Fr_{g\,strat} = 1.5 + (0.2 * WLR_m) \quad \text{-- (24)} \qquad \#A = 0.4 + \{-0.1 * (\exp(-WLR_m))\} \quad \text{-- (25)}$$

$$n_{strat} = \left\{\left(\frac{1}{\sqrt{2}}\right) - \left(\frac{\#A}{\sqrt{Fr_{g,strat}}}\right)\right\}^2 \quad \text{-- (26)}$$

$$n = n_{strat} \text{ for } Fr_g \le Fr_{g,strat} \quad \text{-- (27a)} \qquad n = \left(\left(\frac{1}{\sqrt{2}}\right) - \left(\frac{\#A}{\sqrt{Fr_g}}\right)\right)^2 \text{ for } Fr_g > Fr_{g,strat} \quad \text{-- (27b)}$$

6e. ORIFCE METERS, WET GAS FLOW & THE POINTLESSNESS OF DRAIN HOLES

Even today with literature available on the response of orifice meters to wet gas flow most of industry has little to no understanding on what that response is. Traditionally, when an orifice meter was being applied to a wet gas flow there was an unproven assumption that the liquid would flow as a river and the orifice plate would act as a dam and "hold-up" the liquid. As this was "obviously" going to have adverse effects on the meter someone had the idea of placing a drain hole at the base of the plate to allow the liquid to pass the plate freely. Today, ISO [11] even has rules regards the application of drain holes to orifice plates. There is only one problem with all this. ***It is all nonsense***. Recent research shows drain holes are pointless additions to orifice plates that offer no advantage and one disadvantage.

CEESI has recorded wet gas flow orifice meter data for when the plate did not have a drain hole. This non-drain hole data was described in 2011 by Steven et al [10] where it was shown that the liquid dispersion (i.e. the “flow pattern”) varies with the wet natural gas production flow conditions. The liquid can be dispersed in the flow anywhere between being stratified (i.e. flowing like a river) and entrained in droplets (i.e. annular mist flow), or anywhere in between. Figures 34 & 35 show stills from CEESI videos of these two flow patterns at an orifice plate with no drain hole. In neither case was there liquid “hold-up” at the plate. The gas and liquid phases flowed freely through the normal orifice, as indeed they must for any steady wet gas flow to obey the law of conservation of mass! The liquid cannot continually build up at the plate. As liquid builds up the cross sectional area of the oncoming fluid flow reduces causing the flow to increase in velocity, i.e. increase in gas dynamic pressure. This in turn increases the flows ability to move more liquid through the standard orifice. Therefore, the liquid hold up in front of an orifice plate reaches an equilibrium immediately after a wet gas flow condition is established. The conditions in Figures 34 & 35 were held for twenty minutes. No change in liquid build up ever occurred. So, if liquid cannot significantly build up in front of the plate the question arises, what is a drain hole for?

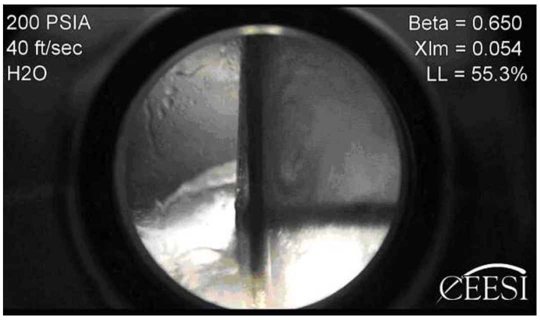

Fig 34.Stratified flow no drain hole.

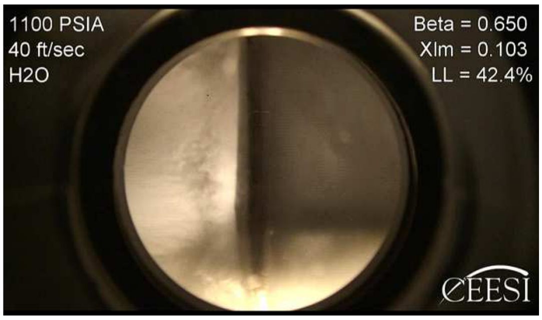

Fig 35.Annular-Mist flow no drain hole.

ISO [10] gives a correction factor for orifice meter with drain hole single phase flow performance. The correction is that equation 28 should produce an effective orifice diameter to be used in the standard orifice meter flow rate equation (i.e. equation 2). There is a single phase uncertainty cost associated with using drain hole. ISO [11] states the drain hole orifice meter uncertainty is calculated by arithmetically adding this additional uncertainty to the normal meters uncertainty. Equation 29 shows ISO’s additional uncertainty prediction for single phase flow.

$$d = d_m \left\{ 1 + 0.55 \left(\frac{d_k}{d_m} \right)^2 \right\} \quad \text{-- (28)} \qquad\qquad 0.55 \left(\frac{d_k}{d_m} \right)^2 \% \quad \text{-- (29)}$$

A plate is given a drain hole when it is to be used with wet gas flow. Drain holes are meant to help the liquid pass by the plate. They are not said to eliminate the significant gas flow prediction errors associated with wet gas flow. Therefore, if an orifice meter with a drain hole is to be used with wet gas flow, and the wet gas flow induces a significant bias on the meters gas flow rate prediction, the practical use of a single phase uncertainty statement is debatable!? If the flow is dry gas you don’t need a drain hole and the added uncertainty in gas measurement is avoidable.

CEESI tested a 4”, sch 40, 0.621 beta ratio orifice meter with a drain hole. The inlet diameter was 4.026”, and the orifice diameter was (d_m) 2.50”. The drain hole diameter (d_k) was the maximum allowed (for maximum effect) at 0.25”. The effective diameter (d) was therefore 2.514” and the additional uncertainty was 0.55%. ISO 5167-2 [1] states the uncertainty in Cd for a standard

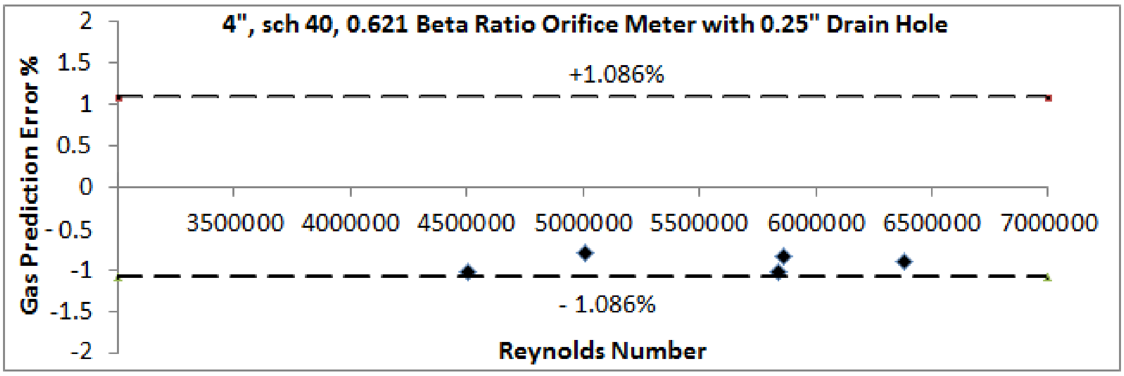

Fig 36. The Dry Gas Flow Results for the Orifice Meter with a Drain Hole.

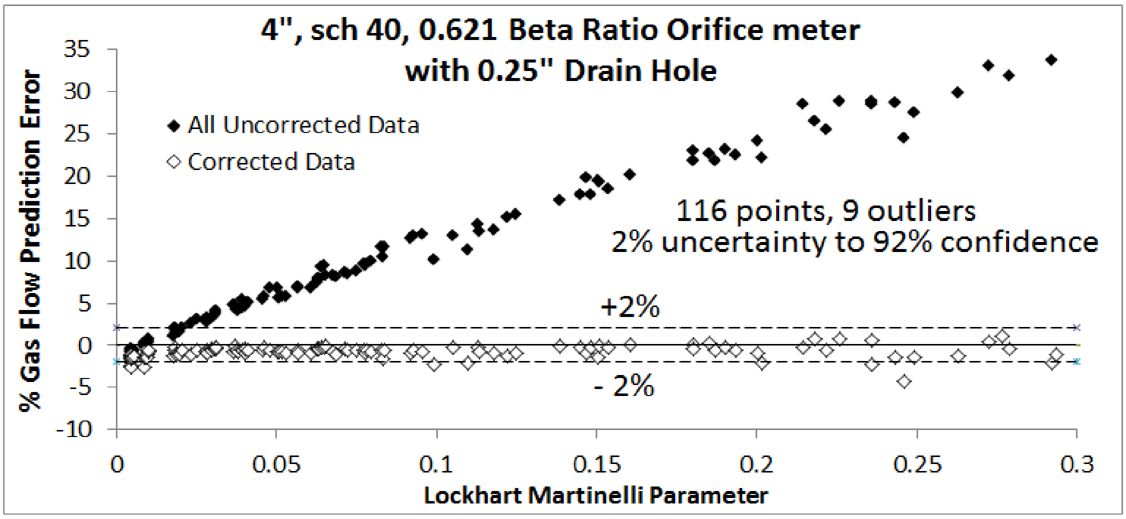

Fig 37. Wet Gas Results for Orifice Meter with a Drain Hole Corrected by Existing Correlation.

orifice meter with no drain hole and a 0.621 beta ratio is 0.536%. Therefore, the overall flow rate uncertainty is > 1.086%. The CEESI result is shown in Figure 36. The dry gas flow rate prediction differed from the reference gas flow meter by (just) less than 1.086% indicating that the orifice meter was operating correctly.

The correctly operating orifice meter with a drain hole was then tested with wet gas flow. The flow conditions were $X_{LM} \le 0.3$, $0.026 \le DR \le 0.083$, $1.75 \le Fr_g \le 4.05$ and $0 \le WLR_m \le 0.77$. The wet gas response of 4" orifice meters with no drain hole are well documented (e.g. Steven et al [10]). Equation set 17, 18, 24, 25, 26, 27a & 27b has been shown to repeatedly correct the standard 4" orifice meters wet gas over-reading to ±2% to 95% confidence. Therefore, orifice meters with no drain hole have a wet gas flow correlation. However, **there is no equivalent correction factor for an orifice meter with a drain hole**. Figure 37 shows the results of applying the standard orifice meter wet gas correlation to the orifice meter with drain hole wet gas data. It is evident that the correlation still works reasonable well. Of the 116 wet gas test points there were 9 outliers, i.e. 2% uncertainty to 92% confidence level, or 2.4% uncertainty to 95% confidence. However, this performance is poorer than for the case of having no drain hole.

In summary the addition of a drain hole significantly increases the uncertainty of the orifice meter with single phase flow. However, the orifice meter with a drain hole is meant to be used with wet gas flow. Drain holes have been traditionally added to orifice meters due to a *false* perception that liquid hold up at the plate is a problem, when it is not. Liquid passes through the orifice plate without a drain hole. The orifice meter with a drain hole has no wet gas correlation! The correlation for the orifice meter without a drain hole must therefore be applied. The resulting gas flow rate prediction has a higher uncertainty than when the meter has no drain hole. So, while drain holes do not significantly aid the passage of liquid past the meter with wet gas flow, they increase the uncertainty of the flow rate prediction in dry and wet gas flow. The question therefore arises, **why are they used!?** The standard orifice meter with no drain hole has a better performance in dry and wet gas flow. Drain holes are a hindrance not a benefit to orifice metering.

7. USE & ABUSE OF THE AMERICAN PETROLEUM INSTITUTE MPMS CHAPTER 22.2

The standards only cover a few DP meter designs. Most DP meter designs are not covered by any standard. The API 22.2 testing protocol [12] was developed to help those DP meter manufacturers whose product was not covered in the standards have a formal method of getting their DP meter design accepted. API's aims in developing this test protocol included:

- Establishing the performance of a DP meter / validating the manufacturers performance claims
- Quantifying the DP meters flow rate measurement uncertainties in different applications
- Providing a comprehensive way to compare different DP meter designs
- Aiding new DP meter technologies market entry with a testing and reporting procedure

A very important point about API 22.2 is that there are no "pass" or "fail" criteria. API 22.2 is just the regulated method of meter testing and report writing. The API 22.2 report simply states whatever the findings from the API 22.2 regulated testing were. It does not judge the DP meter. API 22.2 is neutral to the meter performance. No DP meter tested under API 22.2 has been "certified by API" and API does not approve or disapprove of any DP meter tested under API 22.2. The API 22.2 report gives the unbiased truth about a DP meters performance. It is for the 3rd party reader to make their own judgment to whether the meter meets *their* required performance criteria. Any statement to the effect that a DP meter has been tested in accordance with API 22.2 does not mean the meter has passed some API performance criteria check. Unfortunately, this seems to be misunderstood by some in industry. The following are examples of statements from three different DP meter manufacturers:

1. In one DP meter manufacturer's web site the statement is made that the DP meter has "… API 22.2 certified testing by recognized 3rd party flow laboratories."
2. In another manufacturers brochure it states "… the meter is manufactured in a facility that is ISO 9001, API 22.2-certified…" etc.
3. In a presentation on results of API 22.2 testing, a manufacturer and test facility jointly made the statements that API 22.2 was "… a **standard** defining a testing and reporting protocol." They went on to state "Objectives of the **standard**…"

These are three examples of how API 22.2 is not being fully understood or applied by industry. In the first example the manufacturer states that the meter was tested according to API 22.2. However, this is all that is stated. There is an inherent inference from this stand-alone statement that the meter performed well and is somehow approved by API. This is not true. API only approves of the *method* of testing and reporting. This statement in no way validates the manufacturer's performance claims. It only informs the reader that there must be an API 22.2 report on this meter. To examine whether the meter does indeed meet its published performance criteria the reader must obtain (*and read!!*) that API 22.2 report. It is noteworthy that no associated API 22.2 report was offered on this manufacturer's web site.

In the second example, a different manufacturer directly claims that API has certified, i.e. approved, the DP meter in question. This is a false claim. API does not certify any DP meter with API 22.2.

In the third example, a 3rd party test facility and a DP manufacturer together repeat the claim that API 22.2 is a DP meter **standard**. API 22.2 is not a standard. A standard would infer that the meter has met some stated performance criteria. API 22.2 has no such stated performance criteria and the API 22.2 report is required to discover the true performance of the DP meter. Again there was no mention of where this API 22.2 report on this meter could be obtained from.

The API 22.2 test protocol is a very valuable addition to the flow metering industry. When used correctly the test protocol achieves all the requirements listed in bullet points above and allows DP manufacturers to verify to industry their meters performance claims. However, industry must understand that API 22.2 is not a standard but a protocol to facilitate unbiased neutral testing of a DP meter. **In itself API 22.2 makes no statements regards the performance of the DP meter. It is the API 22.2 report that states the performance of the meter**. Unfortunately some DP meter manufacturers are very forthcoming with statements that the meter has been tested according to API 22.2 (thereby *inferring* API approves of the meter) while being far less forthcoming with the actual API 22.2 report on the result of the testing. When considering a DP meter for an application on the strength of the API 22.2 test protocol, operators are strongly advised to demand the API 22.2 report from the manufacturer. If this report is not forthcoming then the meter manufacturer should not be making a point of telling industry that the meter was tested in accordance with API 22.

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