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Venturi vs. Ultrasonic Meter Comparisons – The Heretical Unauthorized Version

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1 INTRODUCTION

Industry has a wealth of experience with Venturi Differential Pressure (DP) meters (e.g. see Fig. 1). Used for over a century their physical principles of flow measurement are fundamental, well understood, reliable and *beautifully* simple. The development of the popular Venturi meter technology has kept pace with competing flow meter technologies. However, there has been virtually no marketing of Venturi meters in the last twenty years. This has resulted in widespread Venturi meter performance misperceptions. The highly competitive modern Venturi meter performance specifications are hidden in plain sight, described clearly in standards, manuals and text books for the few that care to look, but they are seldom directly compared to competing technologies. Venturi meters are therefore seen falsely by many as old stagnant technology.

Fig. 1 - Venturi Meter

Fig. 2 - Ultrasonic Meter

Industry now has extensive experience with ultrasonic meters, or 'USMs', (e.g. see Fig. 2). Available for more than a quarter of a century their highly competitive performance specifications are well known through years of extensive marketing by multiple corporations. They have been marketed as offering many potential benefits over more traditional flow meters, such as Venturi meters, with three key specifications being:

- a low flow rate prediction uncertainty
- a high turndown (while maintaining a low permanent pressure loss)
- an excellent diagnostic / meter verification ability.

The ultrasonic meter is a marketing triumph as well as a technical achievement. Ultrasonic meters are therefore seen by many as the *obvious* future of flow meter technology. With no significant rebuttal of these claimed performance advantages they have slowly become accepted as axioms, as self-evident truths responsible for the often heard phrase "*… we are upgrading our DP meter to an ultrasonic meter*". To question this widely believed metering doctrine (i.e. dogma) by requesting technical proof, is becoming 'metering heresy'. However, there is a problem. A technical review shows that none of these claimed ultrasonic meter advantages over the modern Venturi meter are actually true.

Although USM proponents may view it as such, this paper is ***not*** meant to be an attack on ultrasonic meters. The authors generally agree with most of the impressive ultrasonic meter performance specifications. The issue is that the modern Venturi meter performance specifications *are just as impressive*. It is the *marketing claims* of the ultrasonic meter superiority that is being questioned. In this paper the modern Venturi & ultrasonic meter specifications are compared. Using mathematics, hydraulic theory, standards, published manufacturer manuals, and 3rd party end user papers the results and conclusions will likely surprise many. Considering the very different physical principles on which these flow meters are based the equally good Venturi & ultrasonic meter performance specifications are *remarkably* similar.

2 ULTRASONIC & VENTURI METER FLOW RATE UNCERTAINTIES

Gas flow must ultimately be metered by mass flow[1] (e.g. kg/hr, MMSCFD[2] etc.). A gas mass flow rate reading is an absolute statement on the quantity of gas flowing in a pipeline. A volume flow rate reading is not. Gas volume flow and gas density both change with the local thermodynamic (i.e. pressure & temperature) conditions, and hence a volume meter's volume flow rate prediction is only applicable at the meter. Therefore, most gas meter designs (ultrasonic & Venturi meters inclusive) require an independent gas density prediction to be available (and trustworthy) at the meter location. Many volume flow meter's ambiguous 'flow rate' prediction uncertainty statements are volume based. This can be confusing, or even misleading. The required mass flow rate prediction uncertainty is higher and often not stated.

A typical generic flow meter's *mass* flow rate prediction uncertainty (ultrasonic & Venturi meter inclusive) is ≤ 0.7%. This may seem *very* high to many, but this is reality. The reader may be used to hearing that an ultrasonic meter has "a gas flow rate uncertainty < 0.2%" but this is a marketing idealised velocity / volume flow rate prediction uncertainty quote, not the actual required mass flow rate uncertainty of most meters in the field.

"There is a lot of uncertainty about uncertainty". Industry follows guidelines laid down by documents such as ISO 5168 [1]. These guidelines advise that an uncertainty analysis should consist of the following steps:

a) establish a mathematical model for the measurement process
b) list & qualify the contributory variances
c) combine variances into a composite statement of uncertainty

While there is agreement on these generic steps, in practice for each specific scenario there is usually debate over what contributory factors need be considered, what the variance of these factors are, and how to mathematically combine inter-connected contributory factors. Such is the case with published flow meter mass flow rate uncertainty calculations. For example, AGA 9 [2] & ISO 17089 [3] both offer worked examples of ultrasonic meter flow rate uncertainty. They have some differences in what contributory variances to include (ISO 5168 part b), and how to combine the varinaces (ISO 5168 part c). This is typical of flow meter flow rate prediction uncertainty calculations. They are all to an extent debatable and difficult to prove.

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1 Strictly speaking natural gas must ultimately be metered by energy content which is achieved by combining mass (***not*** volume) flow and gas composition information.
2 Million standard cubic feet per day (MMSCFD) is a volume of gas at a defined density. Therefore, although MMSCFD superficially looks like a volume flow rate unit it is actually a mass flow rate unit.

Ultrasonic and Venturi meters operate according to very different physical principles. As such their respective uncertainty calculations are quite different, each containing contributory factors only relevant to their own respective unceratinty calculations. Hence, it is difficult to directly compare these uncertainty calculations. It is practically only possible to compare the final output, and there will always be scope for debate regardless of what respective assumptions are used in each meter's uncertainty calculation.

This paper is not dedicated to detailed discussion of ultrasonic & Venturi meter uncertainty calculations. As such, with limited space the authors have chosen to take ISO 17089 Section 7.7 and the orifice meter API 14.3.1 (modified for Venturi meters[3]) as sample uncertainty calculations to be discussed. On such a potentially contentious subject these choices seemed as open and transparent as any.

The aim of this exercise is not to argue over tenths of a percent uncertainties. It is to show that the actual mass flow rate uncertainty predictions of ultrasonic and Venturi meters are remarkably similar.

2a. Ultrasonic Meter Mass Flow Rate Prediction Uncertainty

The multipath ultrasonic meter mass flow rate (Q_m) calculation is shown as equation 1.

$$Q_m = \rho Q_v = \rho A V_{av} = \rho K A \sum_{i=1}^{n} W_i V_i \qquad \text{-- (1)}$$

Note:

- Q_m - mass flow rate (kg/s)
- Q_v - volume flow rate (m^3/s)
- A - inlet area to the meter, i.e. $A=(\pi/4)D^2$ (m^2)
- ρ - fluid density (kg/m^3)
- V_{av} - average flow velocity (m/s)
- K - meter factor (from calibration)
- n - no. of paths
- W_i - weighting factor for path '*i*'
- V_i - measured velocity across path '*i*' (m/s)

The average flow velocity (V_{av}) is predicted by the sum of the products of the individual measured path velocities (Vi) and their corresponding weighting factors (Wi). ISO 17089 Section 7.3.3.5 states "…W_i to W_n, are determined on the basis of documented *numerical integration methods*." Hence, as with all flow meters, Venturi meter inclusive, the actual mass flow rate calculation routine of an ultrasonic meter is complicated relative to the average training of the typical end user. Thankfully, nowadays the complexity of flow meter calculation routines are embedded in the flow computer and the average end user (and even the calibration lab) never has to worry about such detail. However, Equation 1 is shown here to help make sense of the following uncertainty discussion.

Stating that the ultrasonic meter mass flow rate prediction uncertainty is in the order of 0.7% is not the author's opinions, but away from marketing claims, it is published industry wisdom. ISO 17089 [3] Section 7.7 shows two different ultrasonic meter *volume* flow rate uncertainty examples using different scenarios and assumptions. The contributory variances considered by ISO are:

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[3] Considering the long term popularity of the Venturi meter it is curious that unlike ultrasonic & orifice DP meters there are no well-known standard board's Venturi meter flow rate uncertainty calculation examples.

- the reproducibility of the USM as specified by the manufacturer (including all intrinsic factors but excluding the calibration)
- the uncertainty of the calibration facility
- installation effects
- data fitting / calibration curve uncertainty
- other extrinsic factors.

Table 1 - Various Ultrasonic Meter Mass Flow Rate Uncertainty Calculations

contributory variances	Sensitivity Coeff	ISO 17089 example 1	ISO 17089 example 2	Authors moderate example 3
reproducibility	1	0.2	0.3	0.25
calibration facility uncertainty	1	0.2	0.3	0.23
installation influences	1	0	0.3	0.3
calibration data 'K' fitting	1	0	0.3	0.2
handling (other extrinsic factors)	1	0.1	0.1	0.1
RSS % volume flow uncertainty	N/A	**0.300**	**0.608**	**0.505**
Independent Density uncertainty	1	0.4	0.4	0.4
RSS % mass flow uncertainty	N/A	**0.500**	**0.728**	**0.645**

Table 1 shows the two ISO 17089 volume flow rate uncertainty calculations, with the addition of a 3rd moderate example by these authors. ISO consider the reproducibility of an USM to be practically between 0.2 & 0.3% (see examples 1 & 2). Hence the authors consider a reasonable compromise to be 0.25%.

All gas flow calibration facilities have inherent reference uncertainties. As with flow meters, calibration laboratories are in competition to quote ever lower reference uncertainties. However, in practice most industrial grade calibration facilities have mass flow rate prediction uncertainties > 0.25%. In 2010 Zanker et al [4] commented of such facilities: "These have typical uncertainties of 0.2% to 0.3%, so it is difficult [for USMs] to achieve higher absolute accuracies", and "… the product cannot have a stated uncertainty that is better than the laboratory". CEESI Iowa, a leading natural gas flow meter calibration facility, quotes a reference volume flow rate prediction uncertainty as 0.23%. This practical value has therefore been used in the author's example.

AGA 9's [2] Section 7.2.2[4] on installations states that the meter manufacturer should specify the maximum allowable disturbance "…that will not create an additional flow rate measurement error of more than 0.3% due to the installation configuration." It goes on to say: "This recommendation shall be supported by test data" (i.e. 'type testing'). ISO 17089's [3] Section 5.9.3.2 states that the minimum straight upstream pipe length required for the USM to have a maximum additional error due to flow perturbations of 0.3% should be stated. Such is the USM sensitivity to disturbances (i.e. shifts in the velocity profile) that Chan et al [5] state "Operators have to increase their awareness over profile parameters and its influence on [ultrasonic] flowmeter performance." It is advised by AGA & ISO that an USM be calibrated with the upstream & downstream spools in place, with the strong recommendation that the flow conditioner being kept installed in the

[4] At the time of writing, it is being proposed by the AGA9 technical committee that this explicit statement in the main text of AG9 Ed 1 be demoted to an implicit statement in the Appendices in AGA 9 Ed 2. Nevertheless, regardless of this less prominent position in the text, this does not change the fact that USMs should have 0.3% added to their flow rate prediction uncertainties to account for velocity profile differences between calibration and field installations.

same orientation as that of the calibration. Even so various piping configurations upstream of this inlet run & flow conditioner can cause shifts in USM performance, hence the 0.3% additional uncertainty advised by AGA & ISO. This is commented on by Chan [5]: "Even calibrating the [ultrasonic] meter with up/downstream pipe spools and a flow conditioner may not solve the problem, as the profile entering the spool is different between calibration and on-site." Chan goes on to say that "Any non-compensated profile anomally will result in [an USM] systematic [flowrate] mis-measurement." Chan also states that "Operators need to resist the urge to think of the ISO 17089 type test as a guarantee that the [USM] flowmeter performs under all upstream configurations."

As such manufacturers, AGA9 & ISO 17089 state that the USM can be calibrated for any pipework configuration, and in that scenario there would be *no* additional installation uncertainty. However, it is important to realize that this is not a statement / quality specific to ultrasonic meters. The same is true for other flow meters, *inclusive* of the Venturi meter. But, as special pipework configuration calibrations are not the norm for any meter type, USM & Venturi meter inclusive, the authors consider it not representative of the vast majority of cases to ignore the 0.3% installation effect for USMs on the premise that it *could* be (at least partially) calibrated out. It usually is *not* calibrated out. It is therefore fair and representative to keep the 0.3% installation uncertainty component in the generic moderate USM flow rate uncertainty example in Table 1.

The most common method of curve fitting (i.e. 'linearizing') both USM & Venturi meter calibration data is almost certainly "piece-wise linear interpolation". This means fitting a linear line to bridge the unknown between two adjacent calibration points. Figure 3 shows an example of such a practice. This figure uses hypothetical USM data as copied from a hypothetical sample data set given in AGA 9 Section 5.1.2. The piece-wise linear interpolation is shown. This 'data fit' technique (also used for Venturi meters) *by definition* produces a result that appears to have no residual error. However, it is only an *illusion* of no error.

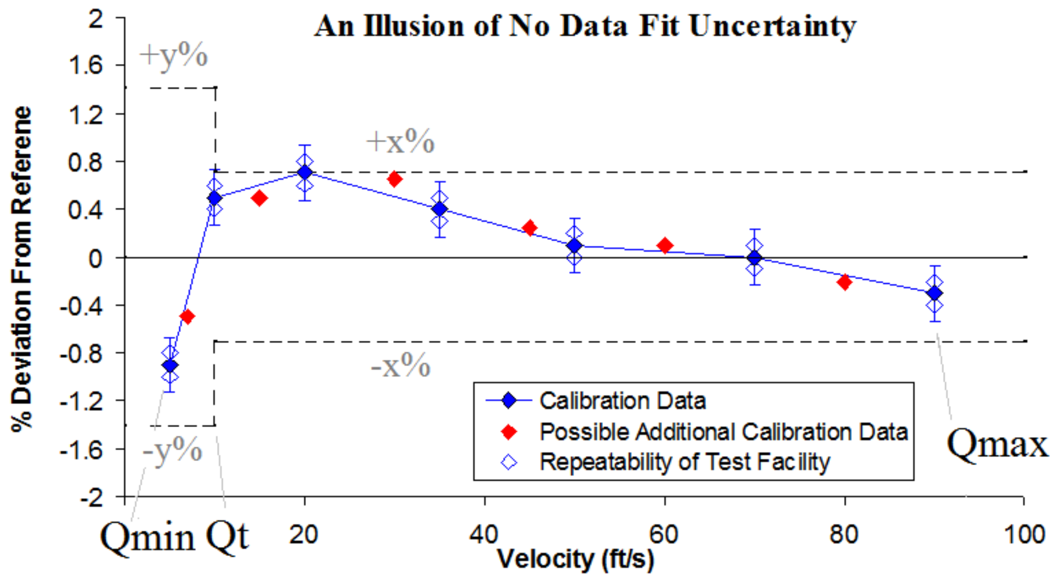

Fig. 3 - Hypothetical Example of Piece-Wise Linear Interpolation

Along with reputable gas flow calibration facilities having a flow reference uncertainty (in the order of 0.25% as indicated by the error bands in Figure 3), they also have a repeatability in the order of ≤ 0.1%. Such repeat points are indicated in Figure 3. (These are slightly simplified, in reality repeat points have repeatability variances in the x & y axes.) The linear fits tend to be between either single points or averages of repeat points, and hence these have an inherent uncertainty of 0.1%. Linear interpolation is defined[5] as "… *an estimation* of a function by *assuming* a straight line between known values". The premise of the linear fits is that when the meter is operated between calibration points the meter performance can be *estimated* by *assuming* the performance falls on this linear line. In reality it is likely to be close to the line, but it is not realistic to assume it will always be on the line. Therefore, it is not realistic to claim that after data fitting a flow meter has no calibration uncertainty (see Table 1 Example 1). When considering the calibration facility repeatability and the limitations of the piece-wise linear interpolation technique, the authors think a calibration data fit uncertainty of 0.2% is realistic and fair (see Table 1 Example 3).

In order to predict the required mass flow rate USMs, like Venturi meters, depend on the gas density being supplied by an independent source. These meter's mass flow rate prediction uncertainty is *wholly* dependent on the gas density uncertainty. ISO 17089's USM examples only predict volume flow prediction uncertainty. The extension to the required mass flow in Table 1 is added by these authors. The density prediction usually comes from a gas chromatograph (GC), with a pressure & temperature reading, & an equation of state / 'PVT' software package (usually AGA8 [6] or GERG [7]). Unfortunately, gas density uncertainty is not widely published or discussed.

API 14.3 [8] suggests this independent gas density prediction has an uncertainty of 0.6%. However, this is undoubtedly a conservative estimate based on obsolete instrumentation and methods. Modern systems should perform better than this. Gas density is calculated by equation 2, where P is the pressure, T is the temperature, R is the universal gas constant, m is the gas molecular weight, and Z is the gas compressibility factor, itself a function of gas composition and the pressure & temperature.

$$\rho = \frac{mP}{ZRT} \qquad (2)$$

AGA 9 Appendix E suggests that reasonable pressure & temperature reading uncertainties are 0.1% & 0.17% at σ =1 respectively. That is 0.2% & 0.34% at σ =2 respectively. Ifft [9] uses a pressure transmitter manual to give an uncertainty example that approximately agrees with this AGA estimate. For a known molecular weight the gas constant is known to an extremely low uncertainty, so practically compressibility is the final component in gas density prediction uncertainty. AGA 9 suggests that compressibility uncertainty is 0.05% to k=1, so 0.1% for k=2. Therefore, the root sum square of the pressure, temperature, & compressibility uncertainties shows that AGA 9 is effectively saying gas density uncertainty is approximately 0.4% at 95% confidence. This is a realistic uncertainty for best practice gas density measurements in the field.

As with *all* flow meter designs the uncertainty of the mass flow rate prediction of an ultrasonic meter is subjective, i.e. dependent on the assumptions made. ISO 17089 gives two examples with different scenarios / assumptions. Through reasoning described above it is seen that the first example is rather optimistic, while the second is rather pessimistic. The authors have argued (not surprisingly) that reality is between these extremes, and a fair and honest ultrasonic gas meter volume flow rate is 0.49% (i.e. approximately 0.5%) and an associated mass flow rate uncertainty specification of 0.645% (i.e. approximately 0.65%).

[5] Merriam-Webster Dictionary

2b. Venturi Meter Mass Flow Rate Prediction Uncertainty

The Venturi meter is a generic DP meter that measures mass flow rate like all DP meters, i.e. by the simple and reliable method of cross-referencing the physical laws of conservation of mass and energy. The Venturi meter uses the generic DP meter mass flow equation set (see equations 3 thru 6). Note equation 3 is ISO 5167-4 2003 equation 1, and the form of equation 6 is shown by ISO 5167-4 2003 equation 2.

$$Q_m = \frac{C_d}{\sqrt{1-\beta^4}} \varepsilon \frac{\pi}{4} d^2 \sqrt{2\rho\Delta P} \quad (3)$$

$$\beta = \frac{d}{D} \quad (4)$$

$$\tau = 1 - \frac{\Delta P}{P_1} \quad (5)$$

$$\varepsilon = f(\beta, \kappa, \tau) \quad (6)$$

Note:

- Q_m - mass flow rate (kg/s)
- β - beta, i.e. diameter ratio, see equation 4
- D - inlet diameter (m)
- d - Venturi throat bore (m)
- ε - expansibility, alternatively denoted by '*Y*', unity for liquids
- C_d - discharge coefficient,
- k - isentropic exponent of the fluid (-)
- τ - ratio of Venturi throat to inlet pressure
- ρ - fluid density (kg/m^3)
- P_1 - inlet pressure (Pa)
- ΔP - differential pressure between inlet and throat (Pa).

The following flow rate prediction uncertainty discussion is based on the API 14.3 orifice meter example modified to be applicable to Venturi meters. The contributory variances to a Venturi meter's uncertainty are:

- uncertainty of the calibration facility
- uncertainty in the expansibility
- data fitting / calibration curve uncertainty
- uncertainty in the independent density prediction
- uncertainty in the DP primary signal reading
- installation effects

Table 2 - Sample Venturi Meter Mass Flow Rate Uncertainty Calculation

contributory variances	Uncertainty (U_{95}%)	Sensitivity Coefficient	(U_{95} S)^2
calibration facility uncertainty	0.23	1	0.053
calibration data 'C_d' fitting	0.2	1	0.040
Expansibility (ε)	0.2	1	0.040
Density (ρ)	0.4	0.5	0.040
DP reading (ΔP)	1.0	0.5	0.250
Sum of Squares			0.423
% Mass Flow Rate Uncertainty			**0.65**

There are differences between the USM & Venturi meter contributory variances. Some differences are only apparent, others are real. This is a consequence of comparing meter designs that work on different physical principles.

Like ultrasonic meters, Venturi meters should be calibrated. Like an USM's inlet area measurement, the Venturi meter geometry measurement uncertainties are systematic uncertainties that are accounted for in the calibration's discharge coefficient uncertainty. Venturi meters are calibrated in the same facilities as USMs. Hence the calibration facility uncertainty is the same, i.e. say 0.23%. Likewise, Venturi meters rely on the same independent density prediction as USMs, and hence the gas density uncertainty is the same, i.e. 0.4%.

The Venturi meter expansibility (ε) uncertainty (U_ε) is quoted by ISO 5167-4 [10] as calculated by equation 7:

$$U_\varepsilon = \left(4 + 100\beta^8\right)\frac{\Delta P_t}{P}\% \tag{7}$$

The uncertainty in the Venturi meter's expansibility is obviously case dependent. Table 3 shows a small sample of expansibility uncertainties. The worst expansibility uncertainties occur with a combination of high beta, low pressure, and high DP. For example, a high 0.7*β* at 25 Bar and a high DP of 1 bar / 400"WC would have an expansibility uncertainty of 0.39%. However, *Venturi meter designers are of course aware of this*, and a geometry is chosen to minimise such increase in uncertainties. In most high pressure, high flow rate, high monetary value natural gas flows expansibility uncertainty is not a significant handicap. Table 3 shows that the mid-beta Venturi meter (0.55*β*) at a relatively low production or transmission pressure of 25 Bar while at a relatively high DP of 1 bar / 400"WC has an ISO predicted expansibility uncertainty of 0.19%. This is typical of the expansibility uncertainty in the field, and 0.2% is used as a reasonable estimate in the uncertainty calculation in Table 2.

Table 3 - Sample Venturi Meter Expansibility Uncertainties

Beta	0.4	0.4	0.6	0.6	0.7	0.7	0.55	0.55
DP (Bar)	1	0.25	1	0.25	1	0.25	1	0.25
P (Bar)	25	100	25	100	25	100	25	100
U exp	0.163	0.010	0.227	0.014	0.391	0.024	0.193	0.012

Some Venturi meter manufacturers (and end users) can and do play the same specmanship[6] games as USM manufacturers (and end users). As with USMs, "piece-wise linear interpolation" is a common way of data fitting Venturi meter C_d vs. Reynolds number data. This suffers the same issues as with the USM. Figure 4 shows a Solartron ISA ISO compliant 6", 0.4β Venturi meter during calibration. Figure 5 shows the resulting real data. The repeat points are shown as hollow diamonds. The average results are shown as solid squares with the linear fits. The triangles show hypothetical points between the real data added by the authors. The error bars show the 0.1% repeatability of the test facility. Again, as with the USM, a reasonable data fit uncertainty for the Venturi meter is therefore 0.2%.

It could be argued that the Venturi meter DP reading uncertainty is equivalent to the USM reproducibility uncertainty. Figure 5 shows that each C_d vs. Re point (solid square) is an average of a set of repeat points (hollow diamonds). This data

[6] "Specmanship'- the linguistic subterfuge used to manipulate data / results in order to improve the apparent specifications of a product or device.

set is typical of Venturi meters with modern digital DP transmitters. These data points repeated to <0.1%, which is comparable to other meter technologies. AGA9 sets the allowable USM repeatability at ≤0.2%, but USM's also typically have a lower repeatability.

Fig. 4 - Solartron 6", 0.4 Beta Ratio Venturi Meter During Calibration.

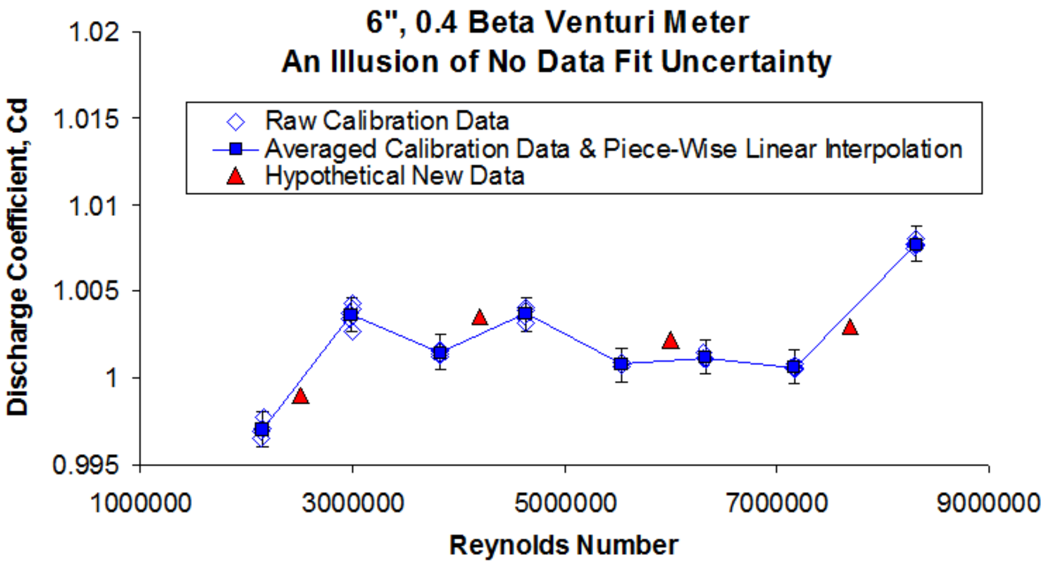

Fig. 5 - Actual Calibration Example of 6", 0.4 Beta Venturi Meter with Piece-Wise Linear Interpolation

The uncertainty of the DP reading is dependent on several factors, including the decision to stack digital DP transmitters, the range of these transmitters, the temperature swing etc. This will be discussed in some detail in section 3 when we consider permanent pressure loss and turndown. The Venturi meter mass flow rate is proportional to the square root of the DP (and density) meaning that a DP (or density) reading uncertainty has half that effect on the mass flow rate prediction uncertainty. For now, let us consider Table 2. In order to achieve a mass flow rate uncertainty equivalent to the USM in Table 1, i.e. 0.645%, the Venturi meter uncertainty calculation shows that the DP uncertainty must be ≤1%. As will be discussed in Section 3, according to most reputable DP transmitter manufacturers this is a very achievable DP reading uncertainty across a wide range of DP.

The USM mass flow rate uncertainty calculation (Table 1) includes a 0.3% uncertainty associated with installation influences. The Venturi meter uncertainty calculation (Table 2) does not. ISO 5167-4 Section 6 [10] produces a table (partly reproduced here as Table 4) showing experimentally found minimum lengths for a Venturi meter, *without* a flow conditioner, installed downstream of common pipe components producing flow disturbances. The lengths stated are those required for there to be *no* change in the Venturi meter flow rate uncertainty. Unlike a USM, a Venturi meter is rather resistant to flow disturbances. When discussing data from Venturi and ultrasonic meters in series, Chan et al [5] stated that they had a "… suspicion that the USMs are influenced by the different in-situ flow profiles, while the Venturi meter is not." ISO 5167-4 Section 6.2.1 says of this matter that "This is due to the attenuation of flow non-uniformities taking place within the contraction section of the classical Venturi tube." Such resistance to flow disturbances is effectively helping prevent the problem that a flow conditioner helps cure, and prevention is generally better than cure.

Table 4 - ISO 5167-4 Required Upstream Lengths (in Multiples of Pipe Diameter) to Ensure No Additional Uncertainty

Beta	Single Bend	Double Bend (in or out of plane)	Reducer 1.33D to D over length 2.3D	Expander 0.67D to D over length 2.5D	Reducer 3D to D over length 3.5D	Expander 0.75D to D over length D	Full Bore Gate or Ball Valve Full Open
0.3	8	8	4	4	2.5	2.5	2.5
0.4	8	8	4	4	2.5	2.5	2.5
0.5	9	10	4	5	5.5	2.5	3.5
0.6	10	10	4	6	8.5	3.5	4.5
0.7	14	18	4	7	10.5	5.5	5.5
0.75	16	22	4	7	11.5	6.5	5.5

The Venturi meters resistance to flow disturbances would be further enhanced if a flow conditioner was added, but in most applications this is not required. Flow conditioners require a significant length of upstream pipe, e.g. CPA advise installing the flow conditioner in a 10D upstream pipe run. Table 4 shows only the Venturi meters with the highest betas combined with the most severe disturbances have a recommended upstream length >10D. In these rare cases a flow conditioner can be installed. Also, as with a USM, if there was an especially difficult installation the Venturi meter could be calibrated with that pipework. However, as with USMs, this is the minority of calibrations. In summary, unlike USMs, there is no automatic required installation uncertainty component required for a Venturi meter flow rate uncertainty calculation.

Hence a fair Venturi gas meter mass flow rate uncertainty specification is in the order of 0.65%. Which leads to a conclusion some in industry may find startling:

A review of ultrasonic and Venturi meters shows both meters have very similar flow rate prediction uncertainties. There is no significant difference between the meters in this specification. Properly calibrated ultrasonic and Venturi meters both have a state of the art gas mass flow rate prediction uncertainty in the order of 0.65%.

3 FLOW TURNDOWN

The operational flow range of a flow meter is described as the "turndown". The turndown is defined as the *ratio* of the largest to smallest flow rate that can be metered to the meter's stated flow rate prediction uncertainty at a stated confidence level. Flow meters, ultrasonic & Venturi meters inclusive, continue to operate below this minimum at higher flow rate prediction uncertainties. Low flows with flow prediction uncertainties that exceed the meter's stated flow rate uncertainty are *by definition* outside the turndown specification.

For operational reasons most natural gas pipelines cap the maximum flow to 30 m/s. Hence, generic natural gas flow meters are seldom designed for continuous flows at >30 m/s. Most gas meter designs, ultrasonic & Venturi meter inclusive, can easily be designed for a nominal maximum of 30 m/s, and hence turndown is in reality defined by how much lower than 30 m/s the meter can read within its stated prediction uncertainty. This general case will be discussed in Section 3a & 3b for ultrasonic and Venturi meters respectively, with the special case of surge flow, i.e. the case where the flow occasionally exceeds 30 m/s for short periods discussed in Section 3c.

3a. Ultrasonic Meter Turndown

Figure 3 shows a hypothetical ultrasonic meter calibration result based on an AGA9 example. Hypothetical uncertainty limits are also shown indicating that uncertainty is dependent on the required turndown. Figure 3 shows that as the flow rate reduces from the maximum (Q_{max}) there is some threshold flow rate (Q_t) before the meter's flow prediction uncertainty of x% rises. From this threshold flow down to the minimum flow (Q_{min}) the flow rate uncertainty is y%, where y%>x%. Whereas AGA9 shows such uncertainty limits for an uncalibrated USM, the universal rule of a reducing measurand resulting in the instrument output having an increasing measurement uncertainty holds for all calibrated flow meters, ultrasonic and Venturi meter inclusive. Hence, as with all flow meter designs different turndown ranges should have different associated uncertainties assigned to them.

The nominal maximum flow rate (Q_{max}) usually corresponds to 30 m/s (i.e. ≈100 ft/s). The ultrasonic meter may be calibrated for higher flow rates in order to give some surge flow capability, but this is not within normal operational parameters, and this scenario will be dealt with separately in Section 3c. As end users do not tend to deliberately run gas at >30 m/s any ability to operate at higher flows is of academic interest only and (with the exception of surge flow) not of practical importance. Hence, any practical turndown statement should be based on this industrially set maximum flow. The threshold flow rate (Q_t) is determined by the USM manufacturer. It is often the flow rate corresponding to approximately 1.5 m/s (≈5 ft/s). The minimum / cut off flow varies, but a common minimum calibration volume flow is that giving approximately 0.75 m/s (≈2.5 ft/s). Therefore, as for a set density and cross sectional area the velocity turndown is equivalent to volume & mass flow turndown, a reasonable turndown for an ultrasonic meter is 30 m/s to 1.5 m/s, i.e. 20:1 at x%, or 30 m/s to 0.75 m/s, i.e. 40:1 at y%, where y%>x%. That is, if the operator wishes to maintain the highest mass flow rate prediction uncertainty across the meter range (i.e. typically of 0.65% at 95% confidence, see Section 2a), the ultrasonic meter turndown is practically 20:1. This is a competitive flow range specification that more than covers the majority of industrial applications.

Unfortunately, as both manufacturers and end users like to keep equipment specifications simple all too often a flow meter's turndown is described as a single ratio with no associated uncertainty & confidence level stated. This has led to USM manufacturers claiming USM turndowns of 40:1 or higher. With no mention of the associated uncertainty the end users all too often falsely assume these high turndowns maintain the low flow rate uncertainty. These inflated turndown claims have led many in industry to claim that an ultrasonic meter's turndown is significantly better than that of a Venturi meter system. However, as we will see this is not in fact true.

3b. Venturi Meter Turndown

A Venturi meters primary signal, i.e. the DP (ΔP), has theoretical parabolic relationship with the flow rate (Q_m), as shown in equation 8. This relationship is a consequence of the physical laws of the conservation of mass and energy and is therefore *precisely* understood. The ultrasonic meter's theoretical primary signal (difference in time of flight, Δt), is linear with flow rate. The authors have repeatedly heard USM proponents claim that the USM derives some (undefined) advantage from this linear relationship compared to the Venturi meter's parabolic relationship. However, in reality, as long as the relationship between a meter's primary signal and the flow rate is precisely mathematically defined there is no theoretical advantage. The only potential practical advantage would be that for a given flow rate range the primary signal's range is wider for a parabolic relationship than for a linear relationship, meaning the Venturi meter primary signal (DP) range can be large. That is, if the Venturi meter's uncertainty is to match that of the USM, this wide DP range must be read to an acceptably low uncertainty, i.e. 1% as shown in Section 2b.

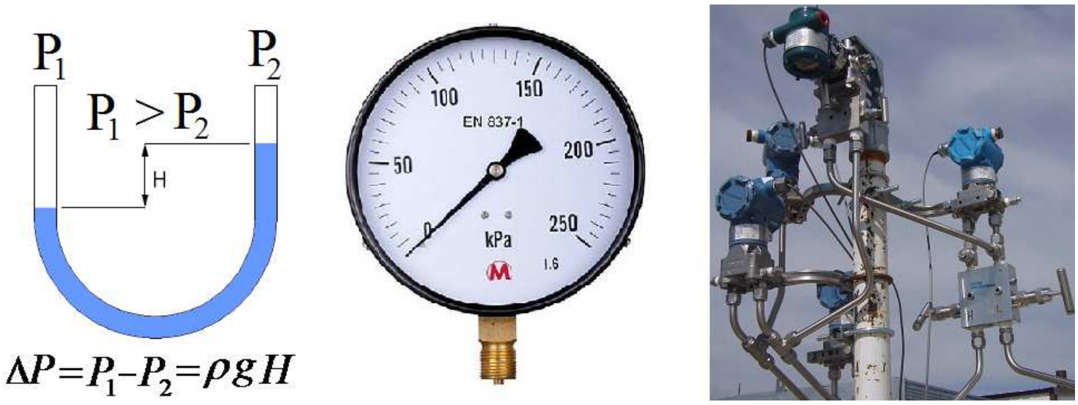

Fig. 6 - Manometer, Bourdon Gauge & Stacked Modern DP Transmitters.

Early Venturi meter systems read DPs by manometer or Bourdon type devices (see Figure 6). These early DP measurement methods had a *DP turndown* of approximately 10:1. This means the maximum measurable DP was ten times larger than the minimum measureable DP. Hence ***early*** DP meters were said to have a corresponding *flow rate turndown* (due to equations 3 & 8) of √10:1, i.e. ≈ 3:1, i.e. the maximum measurable flow rate was three times larger than the minimum measureable flow rate. Hence **long ago**, before the advent of modern instrumentation, before USMs even existed, the Venturi meter *used to have* a flow rate turndown of 3:1. This is where the flawed perception of the modern Venturi meter turndown limitation originates.

$$Q_m \propto \sqrt{\rho \Delta P} \quad \text{-- (8)}$$

In the modern world with stacked digital DP transmitters this limitation has long been consigned to history. One of the most significant (and understated) improvements in flow metering equipment in the last twenty years is the vast improvement of DP transmitters. Modern DP transmitters are designed by some of the same corporations that have developed USMs. Today's digital DP transmitters are individually capable of measuring the same or larger DP ranges more accurately than these archaic traditional methods.

The relatively low cost of these modern massed produced digital DP transmitters makes it in most cases economically attractive to 'stack' DP transmitters rather than consider other more expensive metering technologies. 'Stacking', i.e. adding DP transmitters that are for different DP ranges, is simple and approved by industry, e.g. API 14.3 [8] discusses DP transmitter stacking in its Section 1.12.2. This significantly increases the DP meter's measurable DP range and hence the associated flow rate turndown to an order of magnitude greater than the historic 3:1 turndown. To prove the point we consider a worked example using published DP transmitter manual specifications in Section 3b.1.

First though, note that a Venturi meter's mass flow rate prediction is proportional to the square root of both DP **and** density. Therefore, compared to linear meters like the USM where the flow prediction is linear to density, the Venturi meter flow rate prediction uncertainty is less sensitive to biases in the estimated fluid density. Hence, it is rather disingenuous of USM marketers to claim a practical advantage due to the Venturi meter's flow prediction square root relationship with DP, when the same associated square root relationship with density practically counters any such claimed advantage.

3b.1 Worked example

Consider the flow of a natural gas (with a molecular weight of 18) at 60 Bar & 20^{o}C in an 8", schedule 80 pipe. The density is 49.6 kg/m^3. The maximum expected flow rate is 176 MMSCFD (i.e. a Reynolds number of 26.2e6, a velocity of 30 m/s). A 0.566β Venturi meter is selected and calibrated across the Reynolds number range. The maximum DP corresponding to the maximum flow rate at a C_d of 1.01 is 200 kPa (i.e. 800"WC). What flow rate turn down is achievable using stacked modern DP transmitters? (USM proponents may now be shouting 800"WC!? What about the permanent pressure loss!? We will deal with that fallacy later in Section 3d.)

In order to be realistic let us assume an application where the DP transmitters are outside exposed to a seasonal 28K (50^{0}F) temperature swing. (If a transmitter was housed in a temperature controlled building the DP reading & corresponding flow rate uncertainties reduce significantly.) As the flow rate and the associated DP reduces the uncertainty in the DP reading increases. The modern DP transmitter products all have similar specifications which are stated in their respective manuals. In the following example the Yokogawa EJA product series is used as a generic example of modern DP transmitter capabilities.

Figure 7 shows the DP reading uncertainty if a stack of three DP transmitters are used, i.e. a 'H capsule' upper range limit (URL) of 500 kPa (≈2000"WC) spanned to 500 kPa (), a 'M capsule' URL of 100 kPa (≈400"WC) spanned to 50 kPa (≈200"WC), and a 'L capsule' URL of 10 kPa (≈40"WC) spanned to 5.5 kPa (≈22"WC). The component uncertainties that cannot be 'zeroed out'[7] are combined using root sum square technique (as instructed by Yokogawa).

Yokogawa states uncertainty in 3σ (i.e. 99.7% confidence). To keep these results comparable with the USM results and the rest of the DP meter uncertainty components Figure 7 shows these uncertainties converted to 2σ (i.e. 95% confidence). Table 2 shows that the DP must be read to ≤1%. The transmitters

[7] Long term drift is a universal problem with all flow meters. Here, just as USM drift over the years between re-calibration is an unaccounted for uncertainty, the authors have also not accounted for any long term drift of DP transmitters. For both meter designs these uncertainty component are *assumed* to be small.

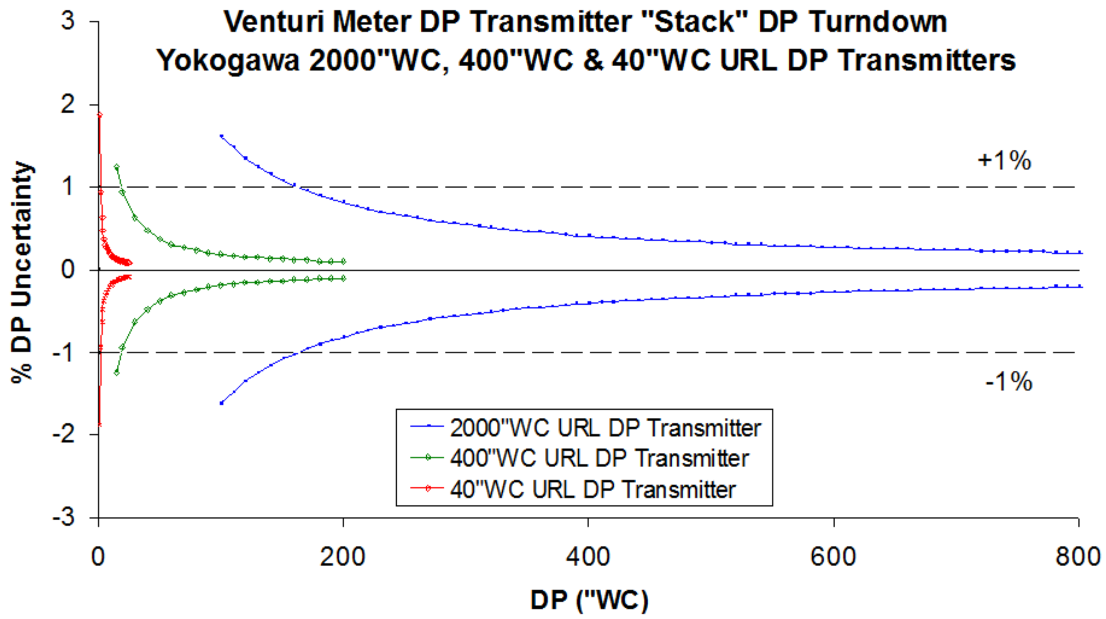

Fig. 7 - DP Reading Uncertainty of Three DP Transmitter Stack

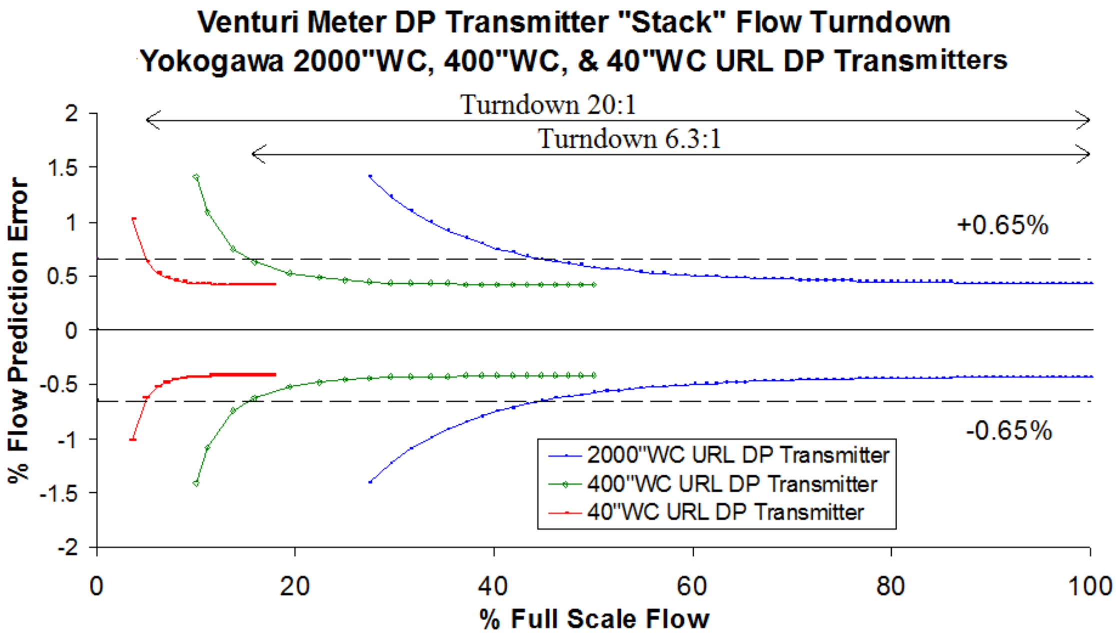

Fig. 8 - Flow Reading Uncertainty Associated With A Three DP Transmitter Stack

overlap such that between the DP range of 200 kPa (≈800"WC) and 0.5 kPa (≈2"WC) the DP is never read to >1% uncertainty. Figure 8 shows the corresponding flow rate turndown for 0.65% uncertainty at 95% confidence. The three DP transmitter stack has produced a 200:0.5, i.e. 400:1 DP turndown at 1% at 95% confidence, and a corresponding flow rate turndown of √400:1, i.e. 20:1 at 0.65% uncertainty at 95% confidence. Hence, with the simple, common, relatively inexpensive, and approved practice of stacking digital DP transmitters, <u>a modern Venturi meter system has the same turndown capability as an ultrasonic meter</u>.

The majority of real applications do not require a huge flow rate turndown range. Often, real applications don't need more than two DP transmitters in a stack. If only the H & M capsules were used, then the DP transmitters overlap such that between the range 200 kPa (≈800"WC) to 4.7 kPa (≈19"WC) the DP is always read to <1%. This produces a 42:1 DP turndown at 1% at 95% confidence, and a corresponding flow rate turndown of 6.5:1 at 0.65% uncertainty at 95% confidence. As we will discuss in 2c, although this may sound like a relatively narrow flow range it is wider than many end users realise and often more than is actually required by industry in many applications.

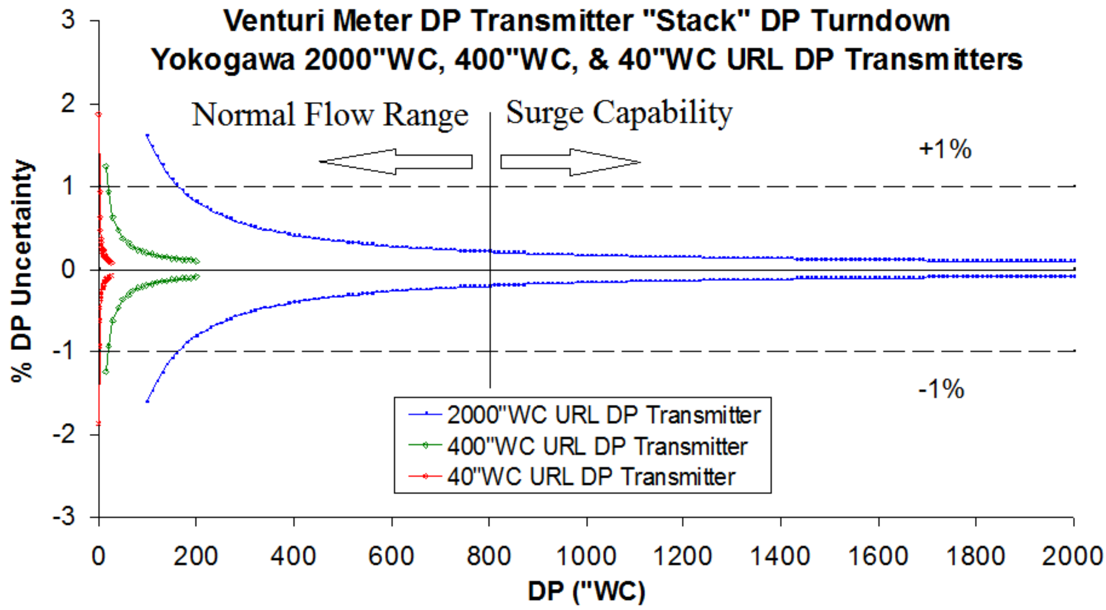

Fig. 9 - DP Transmitter Stack's Capability to Measure Higher Than Expected DPs

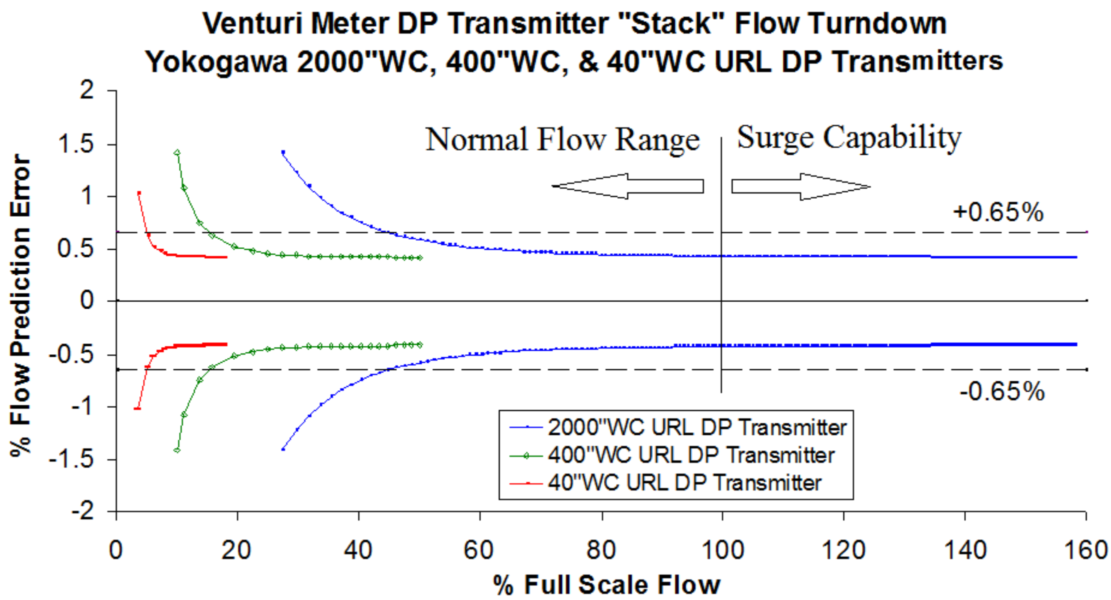

Fig. 10 - Surge Capability of Venturi Meter With a DP Transmitter Stack

The Venturi meter & USM turndown is restricted not by flow meter technology but by the pipeline cap on the maximum velocity. However, it is inevitable that applications may see periodic higher velocities, or 'surge flows'. It is advantageous for a flow meter to continue to operate in this state of 'surge flow'.
The ultrasonic meter marketers make a great play about the USM's ability to cope with surge flows. This is cited as a major selling point of USM technology. It is

common practice for USM calibrations to include calibration points in excess of 30 m/s in case the meter has to cope with surge flow. The typical maximum calibrated flow velocity is about 50% higher than the stated nominal maximum flow velocity, e.g. if a maximum velocity of 30 m/s is expected the USM may be calibrated up to 45 m/s. It is unusual for a USM to be calibrated with significantly higher flows still as somewhere above this rule of thumb limit the USM begins to fail due to excessive background noise, i.e. low signal–to-noise ratio (SNR).

The authors agree that USMs can cope with surge flow well compared to many meter designs, e.g. orifice meters (which may buckle) or turbine meters (where over-speed can damage the rotor bearings). However, no flow meter design, *ultrasonic meter inclusive*, copes with surge flow better than a Venturi meter. In our example, if the flow exceeded 30 m/s, where the DP produced is 200kPa (≈800"WC), the Venturi metering system will continue to operate within the stated performance specification up to a maximum DP of 500 kPa (≈2000"WC), or whatever maximum DP the transmitter is rated for. Figures 9 & 10 show this scenario for the DP and flow rate turndowns respectively. In this case the 3 DP transmitter stack would have a DP turndown of 500 kPa to 0.5 kPa, i.e. 1000:1, which corresponds to a flow rate turndown of √1000:1, i.e. 31.6:1. Figure 10 shows the 'surge flow' capability this provides. In this example the Venturi meter can operate within its stated flow rate uncertainty at >50% more flow than the expected maximum. This is equivalent to USM surge flow capability.

If the end user is concerned about potential surge flow then there are some precautions that can be taken. Although it is common for USM calibrations to include over-speed calibration points this is not a capability unique to USMs. Venturi meter calibrations can also include over-speed calibration points. This practice supplies an accurate discharge coefficient in the event of surge flows. However, if this is not done ISO 5167-4 Table B2 offers approximate discharge coefficient predictions for machined convergent section Venturi meters to a Reynolds number dependent stated uncertainty.

Pipeline maximum flow velocity limits aside, the practical limit of a Venturi meters maximum flow velocity is set by the maximum readable DP and the limit of applicability of the Venturi meter expansibility equation. There are DP transmitter products capable of reading huge DPs so the DP reading limit is set by the choice of DP transmitter. The ISO Venturi meter expansibility equation is applicable when $(P_1-\Delta P)/P_1 \geq 0.75$. In our worked example with an inlet pressure (P_1) of 60 Bar, the maximum ΔP allowed is therefore a *huge* 15 bar. Furthermore, the Venturi meter by design is one of the most sturdy meters on the market that suffers no specific damage concern with extreme surge flow. Hence, there is no practical limitation to Venturi meters potentially metering extreme surge flows. Any implication that a Venturi meter cannot cope with surge flow is rather disingenuous.

A review of ultrasonic and Venturi meter flow rate turndowns shows that both meters have very similar turndowns. There is no significant difference between the meters in this specification. Ultrasonic meters and Venturi meters with stacked digital DP transmitters both have a flow rate turn down in the order of 20:1. Furthermore, both meters can cope well with over-speed / surge flows.

A common way to decry such a description of Venturi meter flow rate turndown capability is to claim that it comes hand in hand with the significant disadvantage of producing a high permanent pressure loss compared to an ultrasonic meter. If this was true it would mean that a Venturi meter would incur significantly more operating expense in the form of gas compression or liquid pumping costs. However, we will see in Section 3d that rather surprisingly this is not the case. First though, it is worth stopping to note that the flow turndown specification of any generic flow meter is often exaggerated by flow meter marketing beyond its true importance.

3c Large Turndown Specifications Are Often Over-Rated

The meaning of 'turndown' is not well understood. Say Meter A has flow range of 100 to 1 units of flow (i.e. 99 units of flow). The turndown is 100:1. Say Meter B has flow range of 100 to 10 units of flow (i.e. 90 units of flow). The turndown is 100:10, i.e. 10:1. Unfortunately, because Meter A has ten times the turndown of Meter B, it is often falsely assumed that Meter A has ten times the flow range of Meter B. It does not! Meter A only covers 90/99 * 100% = 9.1% more range than Meter B. <u>The difference in flow range between 100:1 and 10:1 turndown is not 10 times difference as often assumed but only about 10% difference!</u>

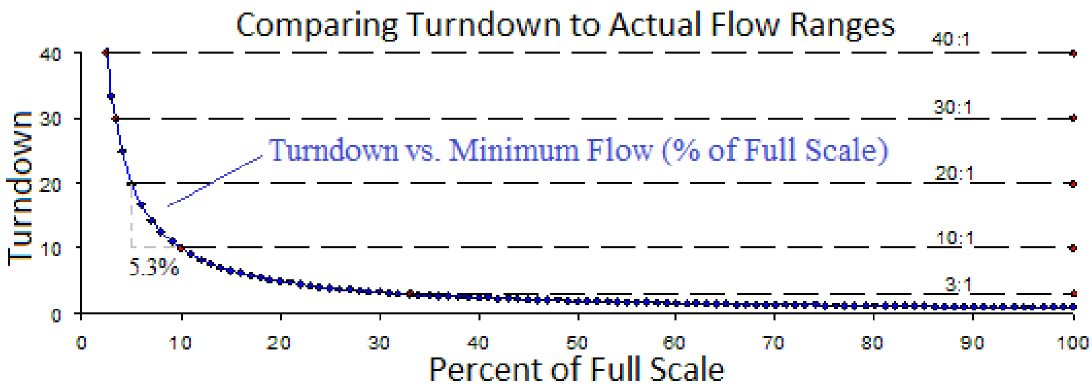

Fig. 11 - Flow Rate Range to Turndown Comparisons

Most flow meters, Venturi & ultrasonic meters inclusive, can be designed for the nominal maximum flow rate (i.e. 100% full scale). The difference in turndown therefore represents how low a flow they can respectively meter within their stated uncertainties. For a set maximum flow Equation 9 calculates the percentage difference in absolute flow range ($\lambda\%$) achieved by Meter A with a turndown of x:1 compared to Meter B with a turndown of y:1, where x>y.

$$\lambda\% = \left[\frac{x-y}{y(x-1)}\right]*100\% \tag{9}$$

Taking the above example of Meter A with a turndown of 100:1 (x=100) compared to Meter B with a turndown of 10:1 (y=10), we see that $\lambda\%$ is 9.1% (as required). Figure 11, graphical representing Equation 9, shows the difference in range between 20:1 (x=20) & 10:1 (y=10) turndowns is not double as is often assumed, but a meagre 5.3%. If we consider the flow range difference in the worked example in Section 3.b.1 between using three or two DP transmitters in the stack, i.e. a flow turndown of 20:1 (x=20) and 6.5:1 (y=6.5) respectively, the difference in absolute range is only 10.9%.

Figure 11 shows that as turndown increases for a set maximum flow rate *a law of diminishing returns* exists. Each step increase in turndown creates a smaller increase in flow range attained. The only practical issue with any meters flow turndown is whether it can cover the required flow range for a particular application, not what maximum turndown a manufacturer claims.

3d Comparison of Ultrasonic & Venturi Meter Permanent Pressure Loss

A full bore ultrasonic meter has no permanent pressure loss (PPL). However, ISO & AGA both repeatedly state the benefits a flow conditioner brings to an USM. For example, ISO 17089 Section 5.9.1 states "In order to achieve the desired meter performance, it may be necessary for the installation designer to alter the original piping configuration or include a flow conditioner as part of the meter run". AGA 9 [2] Section 5.2.1 states "…the use of flow conditioning is recommended to provide the basis for a repeatable and stable metering package". That is, most USM systems include a flow conditioner[8] and therefore most USM systems do have an associated PPL.

ISO 17089 Section 5.9.3.5 states "One of the main advantages of USMs is the absence of a pressure drop. The use of a flow conditioner introduces a pressure drop and negates this advantage." That is, ISO is stating that one of the main *theoretical* advantages of an USM is lost *in practice* by the USM's dependence on flow conditioning. Flow conditioners produce a significant PPL. Therefore, in most cases it is rather disingenuous to claim an USM has no PPL.

A flow conditioner must be installed in an upstream straight run of pipe, e.g., the CPA 50E requires a straight run of ≥ 10D. A USM should therefore have a straight inlet run ≥10D containing the flow conditioner. In contrast, ISO 5167-4's minimum required Venturi meter inlet run lengths to *assure no additional uncertainty* (reproduced here as Table 4) is ≤10D for all but the highest betas with the most extreme disturbances (which is a relatively uncommon scenario). Therefore, if you have ≥10D upstream run length, most Venturi meters in most applications can *and do* operate satisfactorily *without* a flow conditioner. Hence, when comparing the PPL of ultrasonic and Venturi meter systems it is a fair and realistic comparison to consider the USM with a flow conditioner package vs. the stand-alone Venturi meter (with no flow conditioner). However, the examples will consider the Venturi meter with and without a flow conditioner.

Returning to our worked example in Section 3.b.1, let us now consider the PPL consequences of using a Venturi or ultrasonic meter. Most gas flow meters are not continuously run at their maximum nominal flow of 30 m/s, so let us consider the same 8", schedule 80 pipe flow conditions with a gas density of 49.6 kg/m^3 flowing at say, 20 kg/s, i.e. 80.1 MMSCFD, 13.7 m/s, 11.9e6 Reynolds number. (N.B. the relative PPL results are the same regardless of flow rate.) The "minor loss coefficient" (K_{loss}) of pipe components states the PPL (ΔP_{loss}) of that pipe component in multiples of the flow's dynamic pressure, i.e.

$$\Delta P_{loss} = K_{loss} * \frac{\rho V_{av}^2}{2} \quad (10)$$

ISO 5167-1 [11] Annex C states that the minor loss coefficients (K_{loss}) of the Spearman, Zanker, and NOVA flow conditioners are equal to 3.2, 3, & 2 respectively. The Laws / CPA flow conditioner minor loss coefficient is stated by manufacturers to be equal to 2 (at Reynolds number > 100,000). Hence, the NOVA or CPA flow conditioner is the low PPL choice. In this example, the PPL of an USM with a CPA flow conditioner would be:

[8] An USM meter operating without a flow conditioner may have diagnostics that can tell the operator if the flow profile is not as expected, but crucially this only notes the problem, it doesn't correct for it. An USM diagnostic package is no substitute for a flow conditioner.

$$\Delta P_{loss} = 2 * \frac{(49.6)(13.7^2)}{2} = 9.28kPa = 37.3"WC \qquad (10a)$$

Hence, **a USM with a flow conditioner produces a significant PPL**, but how does this relate to the Venturi meter? The Venturi meter is specifically designed to be streamlined, i.e. to be a low loss DP meter. The literature does not directly state the minor loss coefficient of a Venturi meter, but there are other published forms of this information. ISO 5167-4 states that the Venturi meter PPL is accepted as being 5% ≤ DP ≤ 20%. This examples 8", 0.566β Venturi meter with a C_d of 1.01 produces a DP of 40.1 kPa, and hence ISO predicts a maximum PPL of 8 kPa (i.e. 32.2"WC). However, more precise Venturi meter PPL predictions exist. Miller [12] published Venturi meter PPL predictions for 7° & 15° divergent angle diffusers. The Miller equations relate the Pressure Loss Ratio (PLR), i.e. the PPL to DP ratio, to beta, β:

Miller 7° divergent angle diffuser: $$\frac{\Delta P_{loss}}{\Delta P} = 0.218 + (-0.42\beta) + (0.38\beta^2) \qquad (11)$$

Miller 15° divergent angle diffuser: $$\frac{\Delta P_{loss}}{\Delta P} = 0.436 + (-0.86\beta) + (0.59\beta^2) \qquad (12)$$

In the worked example, a 0.566β Venturi meter with a 7° diffuser losses 10.2% of the DP, i.e. a PPL of 4.1kPa/ 16.4"WC. A 0.566β Venturi meter with a 15° diffuser losses 13.8% of the DP, i.e. a PPL of 5.55kPa / 22.3"WC. If a flow conditioner was installed (which is not usually required) the overall PPL would be the sum of the flow conditioner & Venturi meter, i.e. a PPL of 13.48 kPa or 14.84 kPa for the 7° & 15° respectively.

It can be shown that the equivalent minor loss coefficient prediction to Miller's PLR prediction is given by equation 13, where a, b, & c are constants set for a specific beta, e.g. see equations 11 & 12. In the worked example 7° & 15° diffuser Venturi meters (with a C_d of 1.01 & expansibility of 0.995) are predicted to have a minor loss coefficients of 0.88 & 1.20 respectively, with a corresponding PPL of 4.1 kPa & 5.5kPa (as required).

$$\boxed{K_{loss} = \frac{(1-\beta^4)(a + b\beta + c\beta^2)}{(\beta^2 \varepsilon C_d)^2}} \qquad (13)$$

Neither the flow conditioner minor loss coefficient or Miller Venturi meter PLR prediction have a published uncertainty. Figure 12 shows the ISO PLR predicted limits, the Miller PLR predictions, and an approximate interpolated PLR prediction for a 12° diffuser angle. Superimposed on this are sample CEESI PLR vs. β data sets from representative gas flow Venturi meters. All data sets are for a pressure tap at 6D downstream of the diffuser exit. All Venturi meters were calibrated with >10D upstream length but without flow conditioners – as is common practice. All data falls within the ISO predicted range although the data is not particularly reproducible. The black diamonds represent a batch of seven 6", 0.6β ISO compliant Venturi meters with 12° diffusers that are nominally identical. There is a spread between meters of 0.07<PLR<0.107. Nevertheless, this data tends to show that the Miller predictions are conservative. On average the Venturi meter PPL *is slightly less* than the predictions.

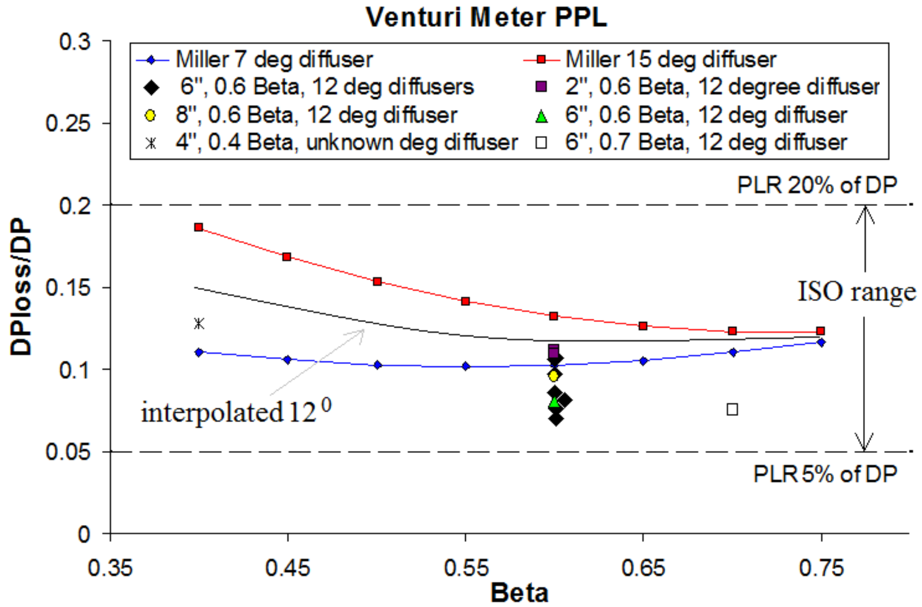

Fig. 12 - Venturi Meter PPL Predictions and Data Sets

Hence, typical Venturi meter systems (without flow conditioners) tend to have slightly less PPL than USM systems. This worked example is not cherry picked. The reader is invited to try such calculations themselves using any flow conditions. The general results will be the same. In hindsight, after considering that a flow conditioner is a perforated plate, whereas a Venturi meter is an aerodynamically designed low PPL converging / diverging tube, perhaps it should not be that surprising that a flow conditioner, and hence the USM metering package, tends to have a higher PPL than a Venturi meter.

A review of ultrasonic and Venturi meter systems shows that both have very low pressure loss characteristics. There is no significant difference between the meters in this specification.

A perception has permeated into industry that a smaller USM does the job of a larger Venturi meter. This belief seems to originate from claims that compared to a generic DP meter the USM has a significantly higher maximum velocity limit and a lower PPL even at that higher velocity limit. But, we have now seen that the Venturi meter has a *similar* maximum velocity limit and similar (or lower) PPL to an USM system. Hence, as a consequence, it is not true to say that a smaller USM does the job of a larger Venturi meter. *For a given flow metering application a USM and a Venturi meter would be the same size*.

4 ULTRASONIC & VENTURI METER VERIFICATION SYSTEMS

Both meter users and manufacturers talk up the concept of flow meter diagnostics to facilitate meter verification, but in practice they are as yet sparingly used. The reasons for this are complex and diverse, and discussed in some detail by Cousins et al [14]. Nevertheless, a comprehensive diagnostic system (or 'suite') is now seen as a prerequisite for a flow meter to be considered a cutting edge, state of the art, modern flow meter. As such, most meter designs are touted as having a diagnostic suite. But not all flow meter diagnostic systems are created equal.

The USM diagnostic suite has been shown to be comprehensive and capable with mass laboratory and field examples. Such is the exposure of the USM diagnostic suite that many in industry assume it to have a better diagnostic suite than *all* competing meter designs. Whereas this is a reasonable proposition when comparing the USM diagnostic suite to those of turbine, Coriolis, & vortex meters, it is certainly *no longer true* of the Venturi (and generic DP) meter. Whereas the Venturi meter is a beautifully simple traditional technology, quite counter-intuitively, it now has one of the most modern, comprehensive, and easy to understand diagnostic suite of all flow meters. This Venturi meter diagnostic system has also been proven with multiple laboratory and field examples (e.g. see Vijay & Rabone [15, 16]). The ultrasonic and Venturi meter both have state of the art diagnostic systems. It is not possible or necessary to give a full description of the USM & Venturi meter diagnostic suites here. All that is possible and required here is a basic summary of each of the meters diagnostic suites. However, before that it is helpful to consider types of diagnostics.

4a Objective and Subjective Diagnostics

Diagnostic techniques can be categorized as either *subjective* or *objective*. In theory and in practice *subjective* diagnostics compare the diagnostic result to an *estimated*, but fundamentally uncertain diagnostic baseline representing a serviceable system. Subjective diagnostics do not offer black & white, yes / no results, but various 'shades of grey' results. An example of a subjective diagnostic technique is monitoring the standard deviation of an instrument reading and comparing it to some rule of thumb baseline value based on experience rather than some physical law.

In theory *objective* diagnostics compare the diagnostic result to a *guaranteed* diagnostic baseline set not by experience but by say a physical law or a calibration result representing a serviceable system. Theoretically, objective diagnostics give black & white, yes / no results. An example of an objective diagnostic technique is check metering, where the physical law of conservation of mass dictates there shall be no difference in mass flow rate predictions between two mass meters in series. However, in practice all diagnostic techniques rely on instrument readings, and all instruments have uncertainty. Setting a reasonable uncertainty limit to instrumentation is a subjective act. Hence, theoretically objective diagnostic techniques are in practice somewhat subjective.

Nevertheless, it is desirable to have a theoretically objective diagnostic technique. The level of uncertainty is then reduced to the instrument uncertainty only. In contrast, subjective diagnostic techniques have both instrument and operator dictated baseline setting uncertainties. In reality all diagnostic techniques fall along an objective / subjective spectrum. Therefore, not all diagnostics are created equal. Thus, a fundamental rule of diagnostics is: **All diagnostic techniques are subjective, but some are more subjective than others.** Unfortunately, with diagnostic interpretation being subjective there is a tendency for some to see what they want to see, and not what is actually there. Or, there is a tendency to claim that the diagnostic system identified a specific problem *after* maintenance had *independently* confirmed the problem source, and they have subconsciously then weaved a narrative fallacy around the diagnostic result and the maintenance report. Nevertheless, generally, the less subjective / more objective a diagnostic technique the more powerful a diagnostic tool it is.

Regardless, all diagnostic techniques are somewhat subjective, and hence the results are by definition interpreted by opinionated end users. It is therefore beneficial to have multiple different diagnostic techniques for the end user to cross reference and therefore build a more confident picture. The Venturi / DP and ultrasonic meter respective diagnostic suites are two of the very best diagnostic suites of all flow meter designs. Both have an impressive blend of subjective and theoretically objective diagnostic techniques where the whole is greater than the sum of its parts. There is no obvious overall diagnostic capability advantage between the two meter designs.

4b Ultrasonic Meter Diagnostic Suite Summary

USMs have a set of paths across which the local flow velocity is found for each, e.g. see Fig 13 for a sketch of a 4 path USM cross section, where the paths (P_n) are between the transducers A & B. The average velocity and hence volume flow is predicted from these velocity measurements across the paths. What's more, the path information tells the operator a lot more than the local velocity.

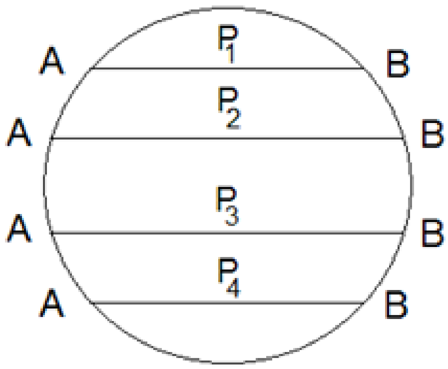

Fig. 13 - A 4 Path USM

The fluid speed of sound is also predicted for each path. This allows a path speed of sound inter-comparison check, and an average speed of sound prediction check against an external speed of sound measurement. The velocity predictions across each path give an idea of the actual velocity profile which can be compared to that of hydraulic theory. Two geometric velocity profile factors used for such a comparison are the profile factor and symmetry.

Each path also has a set of diagnostic tools. The paths "turbulence" is the standard deviation of the velocity (*Δt / path length*) reading . The "gain" of a path is effectively the power required to maintain a clear signal. The paths "signal to noise ratio", or "SNR", is the ratio of the strength of the signal to the background noise. The paths "performance" is the ratio of the number of successful attempts to measure the velocity across the path in a unit time to the number of attempts made. Therefore, there is:

- internal speed of sound measurement comparison (theoretically objective)
- internal/external sound measurement comparison (theoretically objective)
- profile factor & symmetry checks (theoretically objective)
- path turbulence levels (subjective consideration)
- path gain (subjective consideration)
- path SNR (subjective consideration)
- path performance (subjective consideration)

USM diagnostics are often set to a baseline found after field installation as the baseline, or "footprint", can change between calibration and the field. E.g. when describing a real world USM diagnostic example Chan et al [5] stated that the "… [USM diagnostic] footprint as described in ISO 17089 is available, but usually not monitored as even small changes in flow profiles lead to significant changes in the footprint".

There is no standardized USM diagnostic suite presentation. Each USM manufacturer has developed their own form of diagnostic display. Figure 14 reproduces one such display. (The external speed of sound check is not displayed.) Unfortunately, the lack of standardization of the USM diagnostic display has contributed to some end users finding USM diagnostics difficult to understand, as each USM diagnostic display containing fundamentally the same core information can look different and complex. Nevertheless, some end users and consultants can and do use USM diagnostics to great effect. For examples of this diagnostic system in operation see Lansing [17].

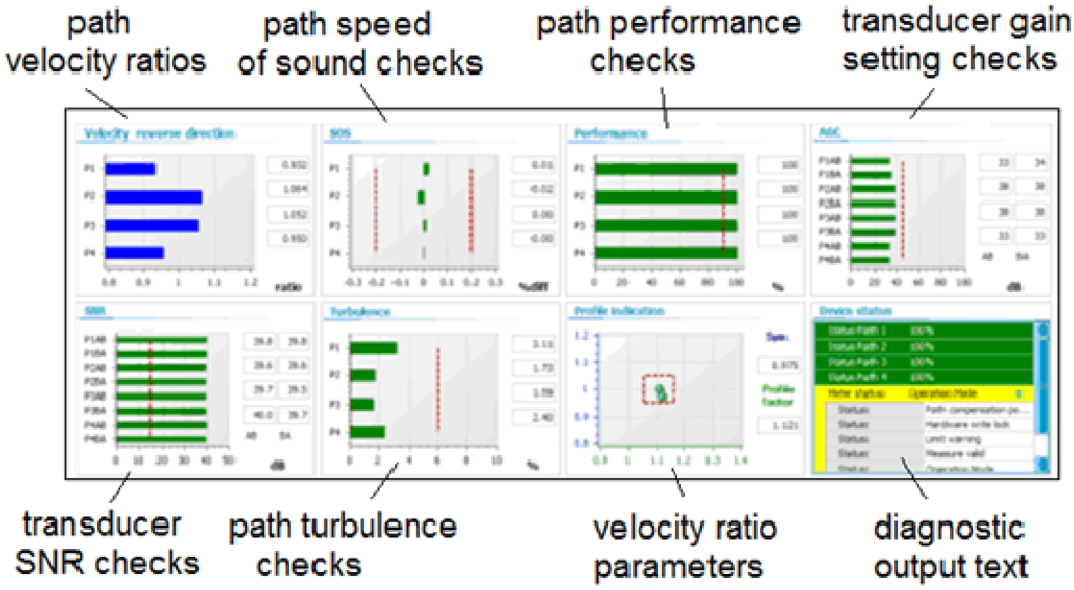

Fig. 14 - Example of a Ultrasonic Meter Diagnostic Screen

4c Venturi Meter ("Prognosis") Diagnostic Suite Summary

Venturi meters can have a downstream tap added, as shown in Figure 15's sketch of a genetic Venturi meter and its associated pressure field. This allows the patented concept of Venturi meter pressure field diagnostics (called "Prognosis"). Three separate DP's can be read, the traditional upstream to throat DP (ΔP_t), the downstream to throat DP (ΔP_r), & the PPL across the meter (ΔP_{PPL}), as shown in Figure 15.

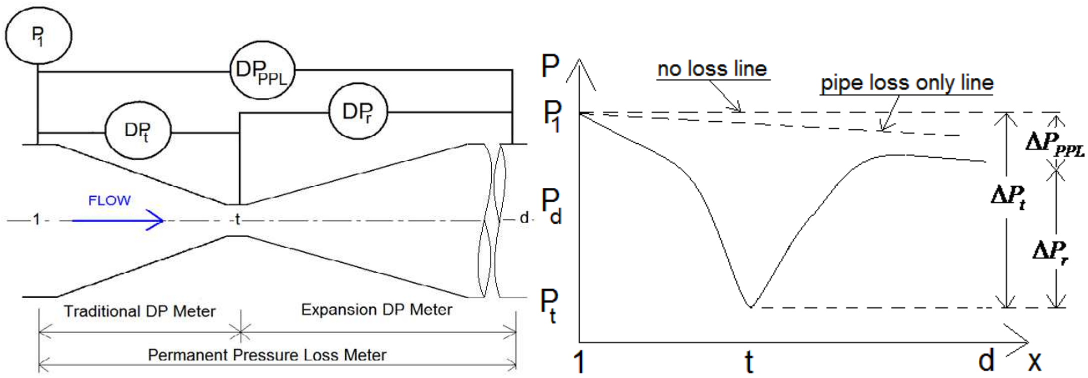

Fig. 15 - Venturi Meter with Instrumentation Sketch and Pressure Field Graph.

These three DPs are inter-related (as shown in Figure 15). It is a consequence of the 1st law of thermodynamics that the sum of the recovered and PPL DPs equates to the traditional DP, i.e. $\Delta P_t = \Delta P_r + \Delta P_{PPL}$. This simple relationship produces an extremely useful DP reading integrity check.

For each of these three DPs an independent flow rate prediction can be obtained. Hence, the Venturi meter effectively becomes the three flow meters in series in one point in space, i.e. the traditional meter (using ΔP_t) has two check meters, the expansion meter (using ΔP_r) and the PPL meter (using ΔP_{PPL}). Conservation of mass dictates that the three flow rate predictions must be the same, and hence comparing the three flow rate prediction pairs give three diagnostic checks.

With these three DPs there are three pairs of DPs, and hence three DP ratios (ignoring the reciprocals). Hydraulic theory dictates that these DP ratios are effectively constant. While the individual DPs change with flow conditions these three DPs change in proportion. Hence, the three as found DP ratios can be compared to their calibrated values to give three diagnostic checks.

Modern DP transmitters have internal diagnostics. This usually consists of a variation on one common theme, namely the standard deviation of the DP signal. Therefore, there is:

- DP integrity / i.e. DP summation check (theoretically objective)
- Expansion / Traditional meter prediction check (theoretically objective)
- PPL / Traditional meter prediction check (theoretically objective)
- Expansion / PPL meter prediction check (theoretically objective)
- $\Delta P_{PPL}/\Delta P_t$ actual to calibration check (theoretically objective)
- $\Delta P_r/\Delta P_t$ actual to calibration check (theoretically objective)
- $\Delta P_r/\Delta P_{PPL}$ actual to calibration check (theoretically objective)
- DP transmitter signal standard deviation levels (subjective consideration)

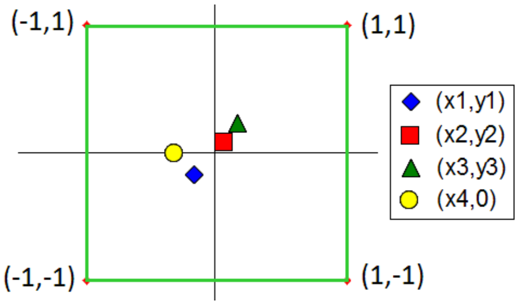

Fig. 16 - Venturi Meter Diagnostic Display

The Venturi meter diagnostic baselines are often set at the calibration. With the exception of the DP reading standard deviation diagnostic check the calibrated diagnostic baseline is transferable to the field. The single subjective diagnostic baseline can be set in the field.

For ease of use the Venturi meter diagnostic display (see Fig 16) is *standardized*. Four points on a graph, i.e. (x_1,y_1), (x_2,y_2), (x_3,y_3) & $(x_4,0)$ represent seven diagnostics results. Coordinates x_1, x_2, x_3 represent three flow rate comparisons. Coordinates y_1, y_2, y_3 represent three DP ratio comparisons. Coordinates x_4 represents the DP integrity check. (The transmitter standard deviation diagnostics are not displayed.) If the points are within the box drawn around the origin then the Venturi meter is serviceable. One or more points lying outside the box indicates the meter is in-serviceable. Industry can and does use Venturi meter diagnostics to great effect. For examples of this see Rabone [16].

A review of ultrasonic and Venturi meter diagnostic / verification systems shows that although the operating principles are very different both are comprehensive. The USM & Venturi / DP meters have arguably the best diagnostic systems of all flow meter designs. There is little difference between the meters in this specification.

It is not possible to directly compare the diagnostic suites of flow meters that operate according to different physical principles. Nevertheless the authors have heard a few comments that imply you can. A relatively common argument is to say that the USM diagnostics can see minor flow profile disturbances and hence are inherently better. But this argument relies on both meters being equally affected by minor flow disturbances. They are not. As the standards imply, USMs are far more sensitive to minor flow disturbances than Venturi meters. Hence, Chan's [5] statement of a "…suspicion that the USMs are influenced by the different in-situ flow profiles, while the Venturi meter is not." So it is imperative an USM diagnostic suite can see minor flow disturbances, while this is not imperative for a Venturi meter. This of course works both ways. A Venturi meter diagnostic suite is good at seeing a DP transmitters leaking 5 way manifold valve. But USMs don't measure DPs and therefore need no such diagnostic capability. In summary, it is not possible to directly compare flow meter diagnostic systems, that would be comparing "apples and oranges". All that can be practically said is a flow meter of a specific physical principle has or has not a good assocaiated diagnostic system. Both ultrasonic and Venturi meters certainly do.

5 ULTRASONIC VS. VENTURI METER IMAGE

Flow meters are required to meter flow as accurately, reliably, and as economically as possible. Flow metering should be influenced by technical and economic facts, and not be influenced by popular trends, fashions etc. Although in reality, to an extent it is. *Everything is*. The influence of peer pressure, perception via marketing, jumping on the bandwagon, not wanting to be controversial, wanting to go with the flow (no pun intended), are universal and of course exist in the flow metering world. USMs have the image of being ultra-modern, exciting, fashionable, slick & futuristic. Venturi meters do not have that image. Hence, regardless of the pros and cons of USMs & Venturi meters, USMs are without doubt currently more trendy than Venturi meters.

Twenty-five years ago the ultrasonic meter *promised a future* of:

- a lower flow rate prediction uncertainty
- a meter that did not require a flow conditioner
- a meter with no permanent pressure loss
- a meter that was so reproducible that it did not require calibration
- a diagnostic system that would identify most problems as they arose
  - and sometimes predict the biases and required corrections.

Today mature ultrasonic meters have only *partially* fulfilled these early promises:

- the flow rate prediction uncertainty is comparable with a Venturi meter
- a flow conditioner is strongly advised by AGA, ISO, and manufacturers
- flow conditioner permanent pressure loss is more than for a Venturi meter
- calibration is required (just like a Venturi meter)
  - with the cumbersome pipe run and flow conditioner included
- the diagnostic system does indicate when *something* is wrong, but for the vast majority of non-metering specialist operators it's difficult to interpret, & generally does not give a precise indication of the cause of alarms or associated metering biases.

Furthermore, Zanker [4], states that such are the challenges facing the USM development that any further improvement in the USM flow rate prediction uncertainty will need to be achieved by incremental advances in different aspects. That is, the days of large jumps in USM specification improvements are over, and further improvements can be expected to be achieved with slow incremental steps.

We have seen that the Venturi meter and the USM have similar specifications, so what is it about the USM that makes it seem so much more desirable: <u>*Marketing*</u>. The USM has a great <u>*marketing*</u> advantage. The USM marketers have done a superb job of promoting the USM. It is a marketing triumph. Through marketing, the USM has an image of being a meter at the cutting edge of technology. Even though the early promise of USMs has not fully materialized the setbacks, such as continuing to require use of a flow conditioner and calibration, have been slow to be realised. They have been countered by the fact that many manufacturers and end users were by then financially, emotionally, and by reputation heavily invested in the USM concept. Curiously, no such technical set back seems to have dampened enthusiasm for the USM concept. After years of having no counter arguments on the behalf of Venturi meters the lines between USM sales pitch and what is taken as actual technical reality are worrying blurred. Nevertheless, the USM is now *perceived* by many to offer many advantages. People can only act on their perception of reality, not actual reality.

The lack of Venturi meter marketing has led to the image of the Venturi meter being an 'old technology', perceived as an unremarkable 'commodity'. It has an image of the 'plain old Venturi meter'. Familiarity has to an extent breed contempt. End users tend not to buy complete Venturi meters *systems* from manufacturers, but rather they buy components and fit (or 'cobble') the Venturi meter system together from the separately bought components, i.e. the Venturi body, DP transmitter/s, tubing, five way manifolds, flow computer etc. All too often the result looks more like an unruly contraption, and not a slick modern flow meter. This problem goes all the way to the standards. ISO 5167-4 is said to be the Venturi meter standard. But if you look at it critically you may realise this is not a complete system document. It is a description of the Venturi meter primary element (i.e. the meter body) and associated fluid flow issues. It says little about the rest of the system, i.e. DP transmitters, manifolds, or the flow computer. However, this is the way industry seems to think of Venturi meters. End users prefer to purchase individual components and install Venturi meter systems. Nevertheless, this does not stop many then saying the Venturi meter is complicated to install, has a large footprint etc. This is in contrast to the USM image.

No end user would contemplate buying USM components and fitting together their own USM system. *Fitting together your own USM would be considered a ridiculous idea*. USMs are purchased as a complete system. They are packaged to have a small footprint, be installed with minimal effort, and be, well… sexy. Not surprisingly the end users like this. But it is the same end users that tend to refuse to consider purchasing similarly packaged Venturi meter systems. *Apparently **not** fitting together your own Venturi meter would be considered a novel idea*. It is only user perception that stops Venturi meter systems being packaged as complete systems equivalent to USMs. This is a legacy issue. At the core of the 'problem' is Venturi meters are so simple, so well understood, that end users feel comfortable fitting together a Venturi meter system. In contrast the USM is much more of a mystery, a black box, and hence they do not feel as comfortable fitting together a USM from its constituent components. *And bizarrely this is seen as a USM pro / Venturi meter con!?*

6 AUTHOR'S EDITORIAL/OPINION

The USM has an image of being superior to that of the humble Venturi meter. Image is powerful, but image is superficial. Real comparisons of flow meters are far more complex than marketing tends to portray. It is relatively easy to prove or disprove the specifications of many mechanical devices, e.g. the maximum weight a crane can lift, or the maximum speed of a vehicle etc. These specifications are very visible, easily observable. This is not so with flow meter specifications.

Flow meters outwardly appear as inanimate objects. Their performance is invisible to the bystander, i.e. not directly observable. Meter performances, and differences in respective meter performances, are only indirectly visible through laboratory calibration, check metering etc. Hence, although meter end users may think they have carried out due diligence when comparing and selecting competing metering technologies, in reality most are not meter subject specialists and it is inevitable that marketing will have a strong influence on them. Hence, often the best marketed meter tends to be favoured. Whether a flow meter actually meets its claimed specifications in service is often difficult to prove, so the end user tends to just *assume* it does. Unfortunately this is even true for many meters with diagnostic systems, as such diagnostic systems cannot be guaranteed to see all small problems, and regardless, many end users just ignore diagnostic outputs. Hence, the *perception* of good performance is in some ways more commercially important than actual performance.

This mindset of USM superiority perhaps derives not just from marketing but also the early (only partially fulfilled) promises of USMs seducing many end user managers to 'hang their hat' on USM technology, and now their reputation is inextricably bound up with USMs. Whatsmore, such was the commerical drive to develop the USM that many engineers were hired into the flow meter industry via USM engineering jobs, and have therefore been conditioned to unquestionably assume the USM as superior.

The agenda for discussing the technological past, present, and future is often set by the promoters of new technologies, in this case USM marketers. For all these USM marketing claims reflect what industry has been repeatedly told, and therefore what they think they know, they are not necessarily as well founded as might be superficially supposed. USMs have been from the outset a highly marketed and intensely discussed technology. As a result it can be argued that the prominence & importance of this technology has been somewhat exaggerated.

Well intentioned efforts to improve technologies can go awry when questionable technical claims are shaped (even subconsioulsy) by commercial interests rather than scientific facts. With a performance equivalent to Venturi meters the USM is indeed an excellent meter. But it is of course a manmade device whose superior performance to more traditional mature technologies should not be treated as preordained. The USM does have pros and cons. Nevertheless, industry seldom discusses USM cons, or in the rare occasions these cons are discussed they tend to be played down. Meanwhile discussions on USM pros abound. This does not give industry a well balance view.

While many may acclaim the qualities of the USM over the Venturi meter there is a dearth of defensible proof that the USMs permeation into the hydrocarbon production industry has significantly altered productivity or reduced costs of hydrocarbon production. Economic historians argue that the significance of a technology is the difference between cost or benefit of using that technology and that of its best alternative. The Venturi meter is an obvious candidate for that best alternative to USMs. Contrary to popular opinion, it is yet to be shown if use of USMs will make industry richer or poorer than use of Venturi meters once *all* costs and benefits are properly accounted for.

Ultrasonic meter proponents may reject these comments out of hand. Cognitive dissonance will no doubt result in some finding these *technical defensible results* preposterous, and worthy of disdain and dismissal. There may be a tendency to want to shoot the messenger rather than seriously consider these facts. The more they have riding on their judgement, the more they are likely to ignore or manipulate any new evidence that calls that judgment into question. The most effective cover ups are not perpetrated by those that are covering their backs, but by those who don't even realize they have anything to hide. But, as John Adams stated "…facts are stubborn things; and whatever may be our wishes, our inclinations, or the dictates of our passions, they cannot alter the state of facts". Reality sometimes delivers painful truths. The state of facts shows that far from the ultrasonic meters being superior to the humble Venturi meter, in reality these competing flow meter types have remarkaby similar capabilties.

7 CONCLUSIONS

Contrary to a widely held belief Venturi and ultrasonic meter mass flow rate prediction uncertainties are on a par. The turndown capabilities and permanent pressure loss characteristics are similar. Both meters have cutting edge excellent diagnostic systems each based on cross-referencing multiple objective and subjective diagnostic methods to give a comprehensive picture of the meter system performance and health. Venturi and ultrasonic meters are *both* state of the art flow meters. Considering the very different physical principles used their performance specifications are *remarkably* similar.

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