North Sea FLOW Measurement Workshop

HYBRID

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1 INTRODUCTION

Flow metering technology has never been so sophisticated and diverse. Advances in electromechanical devices, with their various parameters controlled, operated, and read by ever improving computers have revolutionized flow metering. The last five decades has seen different flow metering physical principles, previously theoretically understood but originally beyond practical application, becoming viable and attractive options for flow meter design. This revolution has produced various robust, reliable, now common place meter 'types' such as Coriolis, transit time ultrasonic, and vortex meters etc. Furthermore, these advances have also facilitated respective real-time verification systems. Nevertheless, all modern flow meter types still have their limitations, signifiacant pros and cons, and industry would benefit from further technical advances.

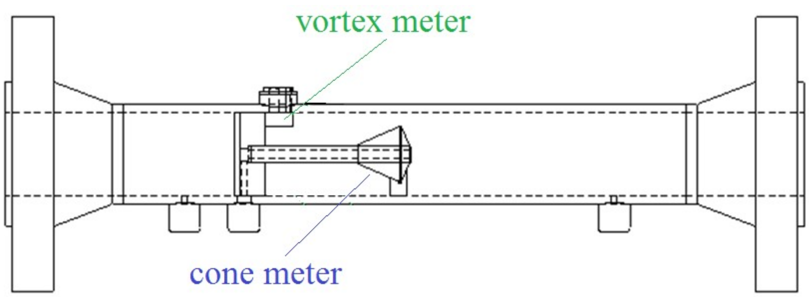

Fig 1. Hybrid Flow Meter Example: Cone and Vortex Meter Combination.

Each of these individual flow meter types, i.e. flow meters operating on a single physical principle, tend to be percieved by flow meter manufacturers and users alike as stand-alone either / or flow metering options. The advantages of using *and* cross-referencing two or more different meter types are seldom considered. Yet, as the science historian James Burke [1] commented "… many inventions, even the brilliant ones, are really no more than putting bits and pieces of existing technologies that were already there, together in just the right way". Therefore, it is arguable that industry is 'missing a trick' by perceiving respective flow meter types as inherently opposing technologies. There are benefits in using multiple flow metering principles together. Modern electromechanical and computer capabilities make it possible to produce practical and economically viable hybrid flow meters where each component meter type is a sub-system of the overall flow meter, e.g. Figure 1, and 'the whole is more than the sum of the parts'. Whereas, some flow metering applications may not benefit from such an increase in complexity, there are various challanging flow metering applications that could.

One obstacle to the advent of hybrid flow meters is that the flow metering industry today is thouroughly balkanized, a Tower of Babel where each flow meter type's subcommunity tend to speak their own jargon. Each such subcommunity can have an incomplete understanding of alternative flow metering technologies. They can suffer from the 'law of the instrument', i.e. an over-reliance on one familiar tool – *their* flow meter type. They may also show unwarrented disdain for competing metering technologies. But in reality, all flow meter types maintain market presence as they all have pros and cons, each fill some niche application/s. If they didn't they wouldn't survive on the market. A little heard truth is that for many flow metering applications any one of several different flow metering principles (or 'types') could be used, and they would each work satisfactorily. So, hybrid flow metering designs will work, but they will only be accepted once manufacturers and users accept that different flow meter designs can be equally respected. And, when used together correctly they potentially produce a far more powerful and capable flow metering system than any single flow meter type deployed alone.

In 2018 Marshall [2] proposed using modular 'multi-parameter measurement devices', to reduce maintenance and calibration costs while 'increasing efficiency'. The authors have long shared these sentiments. These authors advocate the cross-referencing of different metering principles not just to improve on existing capabilities, but to derive new metering capabilities beyond that which is available with standard metering systems. As an introduction to the general concept this paper gives three examples the authors have worked on over the last decade.

3. DABBLING WITH COMBINING FLOW METERING TECHNOLOGIES

Industry may not widely embrace the idea of hybrid flow meters, i.e. the combination of dissimilar flow meter types into a single meter design, but conversely, industry widley embraces the idea of check metering with two stand-alone dissimilar flow meters in series in close proximity. To an extent this is a double standard, although admittedly there are some differences.

Fig 2. 8" Check Ultrasonic Meter Upstream of a Primary Turbine Meter.

Figure 2 shows an example of dissimilar flow meter check metering. There is a primary turbine flow meter with a check ultrasonic flow meter. The concept of check metering with independent dissimialr flow meter types is simple enough. If everything is in order the different flow meters will 'agree' on the flowrate, thus assuring the end user all is probably well. However,if flow meter operations are not in order (due to flow meter component failure or adverse flow conditions) the flow meters will probably disagree, thus alerting the end user to a problem.

Dissimilar meter designs are preferred to reduce the liklihood of a common source problems (e.g. wet gas flow, contamination, erroneus fluid property inputs etc.) causing two simmilar meter designs to have similar flow prediction biases, thereby causing both meters to give the same erroneous result, thereby masking the problem. Not that use of dissimilar meters is an ideal solution. There can still be common source problems, just less of them. For example, if an erronoeous gas density is supplied to a turbine and ultrasonic meter pair, both will have the same unidentified mass flow prediction bias. Use of dissimilar flow meters doesn't *absolutely* assure the user that all is well, there are still inevitable blind spots[1]. But the crucially, use of dissimilar flow meters makes common

[1] Flow meter manufacturers therefore promote the use of individual meter type diagnostic powered verification systems, although for a multitude of reasons, some practical, some ignobile, industry has been extremely slow on adoption of such technology, see Cousins et al [3].

source problems far less likely, and inherently offers more and varied nuggets of information, which when combined and analyzed results in a far more illuminating view of the situation. Nevertheless, this extra information is usually only informally utilised by highly skilled users. Selodom if evert is there any formal software carrying out cross technology checks to fully utilize this latent capability.

Check metering with dissimilar flow meters is widely approved. For example, a German flow meter verification law [4] includes use of dissimilar meters in series to extend calibration periods to as long as both meters have a certified design ('type approval'), both meters are initially calibrated, and they agree within 0.5%. However, whereas stand-alone flow meter verification (powered by flow meter diagnostic systems) is allowed, it doesn't yet automatically replace the traditional practice of check metering. Industry still trusts dissimilar meter check metering. Industry's conservatism extends to these dissimialr meters being independent, each a separate certified type approved design. However, industries preference of two *dissimilar* meters in series shows that it is inherently understood that two different physical principles applied once are fundamentally better than one physical principle applied twice. Hybrid meter designs offer the chance to harness such advantages in one compact meter package.

Proven hybrid flow meter designs offer similar advantages to two dissimilar stand-alone flow meters in series, and indeed potentially more advantages. They potentially have less footprint, could be more economcial to operate, and active software cross-referencing the separate metering sub-systems could make the metering system more capable. However, due to various presuppositions, hybrid flow meters are generally not considered. These presuppositions include the ideas that hybrid meters would be contraptions, the flow metering sub-systems won't work as reliably togeher as they do alone, one flow meter type is superior to the other, they will cost twice that of a single physical principle flow meter, or even two independent flow meters in series, they require complex maintenance etc. As a result, hybrid flow meters are largely unproven, not researched, not designed, not developed, not tested, not certified, and not type approved.

It is now argued that these presuppositions are not necessarily true. Modern electromechancal system and flow computers are remarkably capable and adaptable. For all there are significant challenges in designing hybrid flow meters for the general benefit of industry it can be and arguably should be done.

4. WHAT CONSTITUTES A "HYBRID FLOW METER"?

What constitutes a 'hybrid' meter is subjective. The definition of (the non-biolgical meaning) of 'hybrid' is: 'Produced by a combination of two or more distinct elements'. So what constitutes 'distinct' elements?

Figure 3. Check Metering with Two Ultrasonic Meters in Series

For all industry theoretically prefers check metering with dissimilar flow meters, in reality it is often carried out with similar flow meters. Figure 3 shows an ultrasonic meter example. This compromise can be attractive as users can then standardize on one meter type, simplifying procurement and maintenance, while the operators get more skilled with their extensive experience of using that specific meter type only. Hence, compromising by using similar meters comes with technical disadvantages, but it also offers practical advantages. This imperfect but convenient practice is encouraged by influencial flow meter manufacturers, who driven by both the law of the instrument and sales targets, covet both primary and check meter sales.

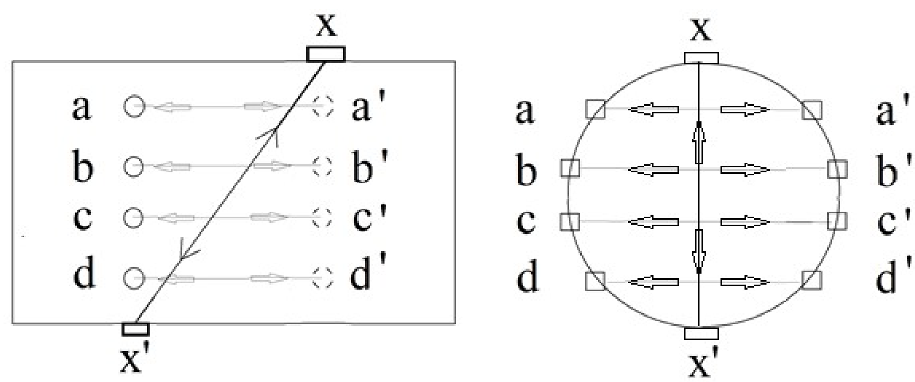

Figure 4. Example of a Four Path Plus One Path Ultrasonic Meter/s Design

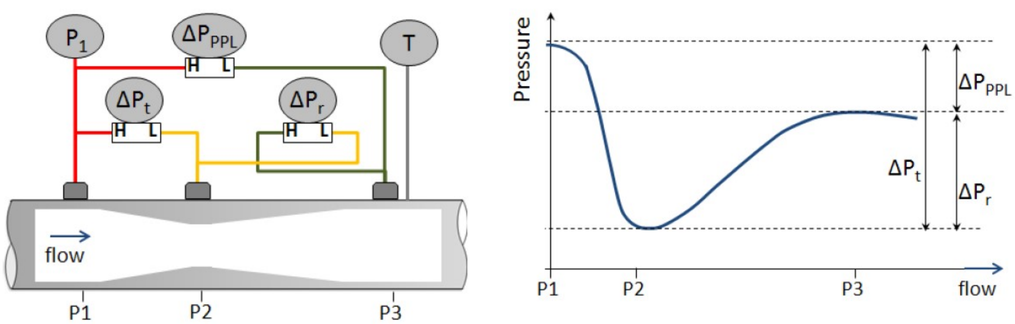

Figure 5. Multiple Differential Pressure Meter Designs in One Meter Body.

A natural evolution of this practice is evident with various flow meter manufacturers now incoporating more than one version of their single physical principle metering system into a single meter body. That is, some flow meter manufacturers are now 'doubling down' on their chosen technology. For example, some ultrasonic meter manufacturers embed more than one ultrasonic meter system within a single ultrasonic meter body (see Figure 4). Another example is DP Diagnostics, who embed multiple pressure field flow meter designs within a single DP meter body (see Figure 5). Technically, these flow meter designs use different physical configurations to apply these extra system/s, i.e. different ultrasonic path or DP tap locations respectively. It could therefore be argued that these respective extra systems represent different 'distinct elements', and hence these designs are hybrid meters. But few do argue so, including the meter manufacturers. Most consider hybrid metering to mean the close quarter combination of distinctly different flow metering principles, not the close quarter combination of different versions of the same flow metering principle.

5. RULES FOR CREATING A HYBRID FLOW METER

It is more difficlut to produce a successful hybrid flow meter than it may first appear. The devil is in the detail. There are three underlying inter-related rules. These may seem obvious, but they are really only obvious once they are enunciated, or in hidsight after failed attempts, as we will see when considering early industry attempts. The rules of hybrid meter design are:

Rule 1: Each flow meter principle used in a hybrid design must be treated with the appropriate consideration for it to function adequately.

Rule 2: Each flow metering principle used in a hybrid design must have a similar flow range to the other flow metering principles used in that hybrid meter design.

Rule 3: Each flow meter principle used in a hybrid design must not adversely effect each other's performance when in close proximity to the other.

These rulesfor designing a hybrid meter design may sound obvious and simple, but they are not at all simple to comply with:

Rule 1: The law of the instrument can and does tend to make researchers and developers favour one 'first' or 'primary' meter design. Thus, the 'second' meter design can tend to be treated as an add on, cobbled together around the 'primary' metering system, with its performance thus compromised. And, even if designers do actively attempt to treat both metering sub-systems equally, the act of combining them into a single meter body often still results in one meter more than the other having its performance compromised.

Rule 2: Each individual meter design has a distinct geometric design vs. flow range calculation (commonly referred to as the flow meter 'sizing'). Hence, a specific flow meter is geometrically designed to cover a specific flow range. However, with hybrid meters the individual meter sizings can be compromised. It may not be possible to size one meter in a potential hybrid meter design without inadvertently adversely influencing the sizing of the other.

Rule 3: Most flow meters require undisturbed flow at the inlet. Intrusive meter designs inherently disturb flow. Hence, an intrusive meter design can potentially adversely affect the performance of the flow meter/s it is paired with.

Nevertheless, the art of designing an economically viable capable hybrid meter requires these rules are followed.

6. A HYBRID MASS FLOW METER CASE STUDY (EXAMPLE 1)

Mass flow metering is generally considered to be metering mass flowrate without an external fluid density input[2]. The term 'mass flow meter' has become synonymous with Coriolis meters. The other well known mass flow meter designs have limited applications, e.g. sonic (or 'critical') nozzles / Venturi meters are laboratory based only, and thermal mass meters are generally seen as inexpensive low accuracy meters. But there is another alternative design.

In 1953 Boden et al [5] advocated the cross referencing of density sensitive and density insensitive volume flow meters, i.e. a hybrid flow meter. This produces a volume flowrate, density, and mass flowrate output, i.e. a mass flow meter. Equation 1 represents the volume flowrate algorithm of a volume meter such as a turbine or vortex meter. The symbol 'Q_v' represents the volume flowrate at line conditions. The symbol '*f*' denotes 'some function'. The symbol 'f' represents the meter pulse frequency primary signal, while the symbol 'K' represents the calibrated meter factor. Hence, the volume flow meter predicts the volume flowrate without knowledge of the fluid density 'ρ'.

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[2] Some volume flow meter manufacturers incorporate a PVT / equation of state gas density prediction into their flow computer (or 'head') and market the resulting system as a 'mass flow meter'. However, whereas the definition is subjective, industry tends to define mass flow metering as direct metering of mass flow *without* the requirement for a PVT / equation of state system.

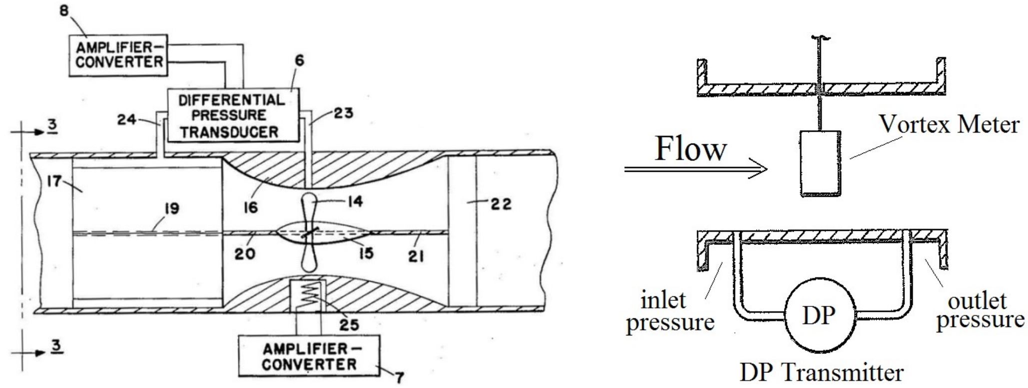

Figure 6. Boden et al, Turbine + Venturi Meter Circa. 1953, and Lisi et al Vortex + DP Meter Circa 1974.

$$Q_v = f(f, K) \quad \text{-- (1)}$$

$$Q_v = f(\rho, \beta, A_t, C_d, \Delta P) \quad \text{-- (2)}$$

$$\rho = f(f, K, \beta, A_t, C_d, \Delta P) \quad \text{-- (3)}$$

$$Q_m = f(Q_v, \rho) \quad \text{-- (4)}$$

Equation 2 represents the volume flow rate algorithm of a differential pressure 'DP' meter. The symbols 'β' and 'A_t' represent known meter geometry values. The symbol C_d represents the DP meter's calibrated discharge coefficient (i.e. meter factor). The symbol ΔP represents the DP meters read primary signal. The DP meter's volume flowrate prediction is density (ρ) dependent. As a stand-alone flow meter the DP meter requires the fluid density input to find the volume (or mass) flowrate. However, Boden showed that if these respective flow meter are in close proximity in series, or components of one hybrid metering system, inputting the volume flowrate prediction to the DP meter algorithm produces a fluid density prediction, see Equation 3. And with the volume flowrate and fluid density thus known the mass flow rate is also then known, see Equation 4. But, the devil was in the detail. It is easier said than done. Lack of flow computers in 1953 made implementing such a system difficult. But regardless, the Boden suggested hybrid meter design violates all three hybrid meter design rules.

Figure 6 shows Boden's hybrid flow meter. The turbine (density insensitive) volume flow meter is placed in the throat of the Venturi (density sensitive) flow meter. The turbine meter is effectively a reduced bore design and should work well across a wide flow range. However, the Venturi meter is compromised. A turbine rotor occuppies it's throat (violating rule 1) thereby potentially affecting the stability of the DP signal (violating rule 3). Furthermore the Venturi meter throat diameter is dictated by the turbine meter geometry and not the Venturi meter sizing, thereby compromising the Venturi meter flow range (violating rule 2). In 1967 Pfrehm [6], attempted to improve Boden's design, but the design was fundamentally similar and still violated hybrid meter design rules.

In 1974 Lisi [7], considered a vortex (density insensitive) meter with the vortex meter's bluff body used as a DP (density sensitive) meter's primary element, see Figure 6. The vortex meter is unaltered and unaffected by the hybrid meter design. However, the DP meter is formed by using the non-optimal bluff body as the primary element (thereby violating Rule 1). The DP for a given flowrate produced across a vortex meter bluff body is very low. Hence, unlike the vortex meter, the DP meter only operates at high flowrates (thereby violating rule 2). Furthermore, the DP meter low pressure tap is in the vortex shedding zone meaning the DP stability is questionable (thereby violating rule 3). In 1984 Mottram [8], attempted to improve Lisi's design with a vortex meter in a nozzle meter's throat. However, the design still violated hybrid meter design rules.

Hence, over thirty years the Boden hybrid mass flow meter concept was periodically revisited but, due to both lack of suitable computers and cognition of the underlying hybrid meter design rules, the concept did not gain traction. However, this does not mean the underlying concept is flawed, or it is not worth further consideration. Nevertheless, after Mottram there was a two decade hiatus and by the 2000's flow meter practitoners had never heard of the concept. Contrary to popular belief, most inventions never make it to industrial use, and are then effectively un-invented. They are not researched and developed, and are forgotten and often lost. Such was the case for Boden's hybrid flow meter design. And so, in 2005 Damarco S. et al [9], and again in 2006 this author (Steven R et al [10]), yet again 're-invented' Boden's concept, each unaware of the numerous prior art.

6.1 An Operational Boden Type Mass Flow Meter

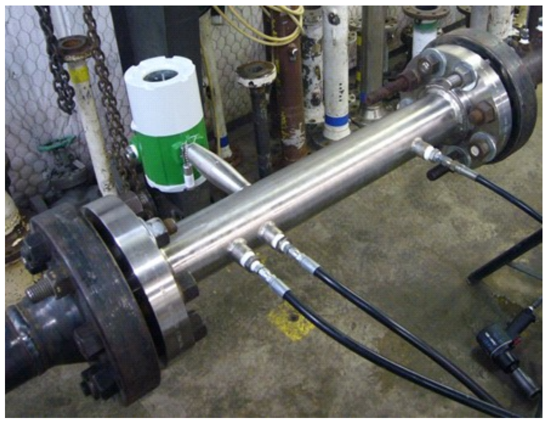

Fig 7. 3", 0.68β VorCone Meter During Air Flow test at CEESI.

Figure 1 shows a vortex (density insensitive) volume flow meter and cone DP (density sensitive) volume meter hybrid design (called a 'VorCone' meter). In 2015 Sanford et al [10] described the development of this Boden style metering concept. The design took multiple iterations as the designers slowly learned the rules of hybrid flow meter design by trial and error. The design in Figure 1 is now a operational practical Boden style hybrid mass flow meter first installed in industrial use six decades after Boden's first disclosure. Here, as so often in industry, there is a very long gestation time between initial inventive ideas and practical equipment being used in industry. Note that:

- The vortex bluff body doubles as the cone support, but unlike standard cone meters this bluff body / strut runs the length of the diameter. It has to. Bluff bodies that terminate in the pipe (and not at the opposite wall) have tip effects that disrupt vortex shedding (which would violate Rule 1).

- The vortex shedding sensor is upstream of the cone. It has to be. The cone influence attenuates the vortex signal (which would violate both Rules 1 and 3).

- The vortex meter is upstream and operates as a standard vortex meter. The cone meter only differs from a standard design by an unorthodox support strut and an extended distance between the support and cone. This does not affect the cone DP meter performance. Rule 1 is satisfied.

- This design *decouples* the sizing of the vortex meter and cone meter. The cone meter flow range is dictated by the cone size, and in this design the designer is free to choose the best cone size unhindered by the presence of the vortex meter. Hence, the vortex and cone meters can be designed to have similar flow ranges. Rule 2 is satisfied.

- The vortex meter is upstream and unaffected by the cone meter. The cone DP meter is known to be disturbance resistant. It is immune to the bluff body flow disturbances. Rule 3 is satisfied.

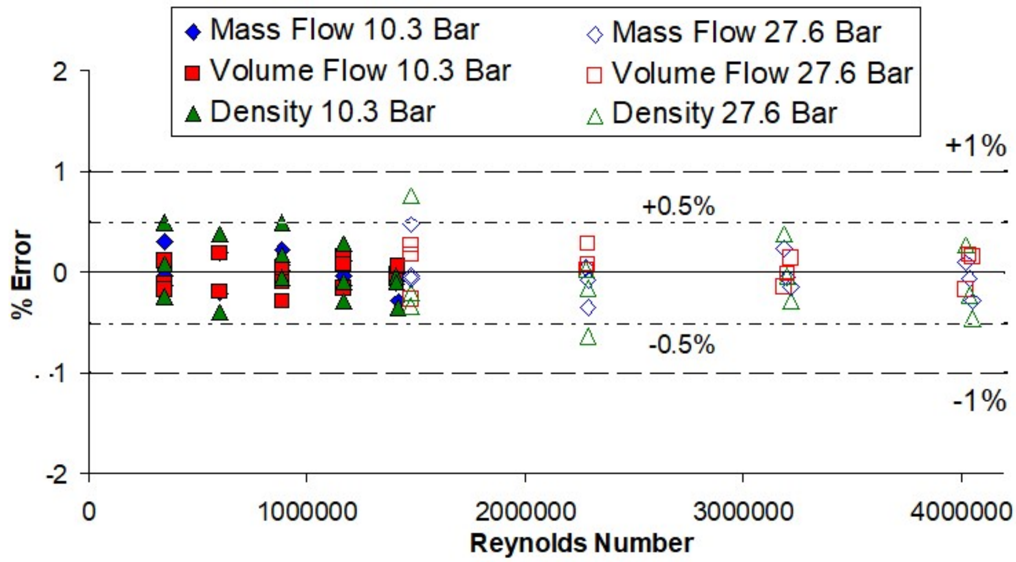

Figure 8. 3", 0.68β VorCone Meter Mass, Volume, and Density Results.

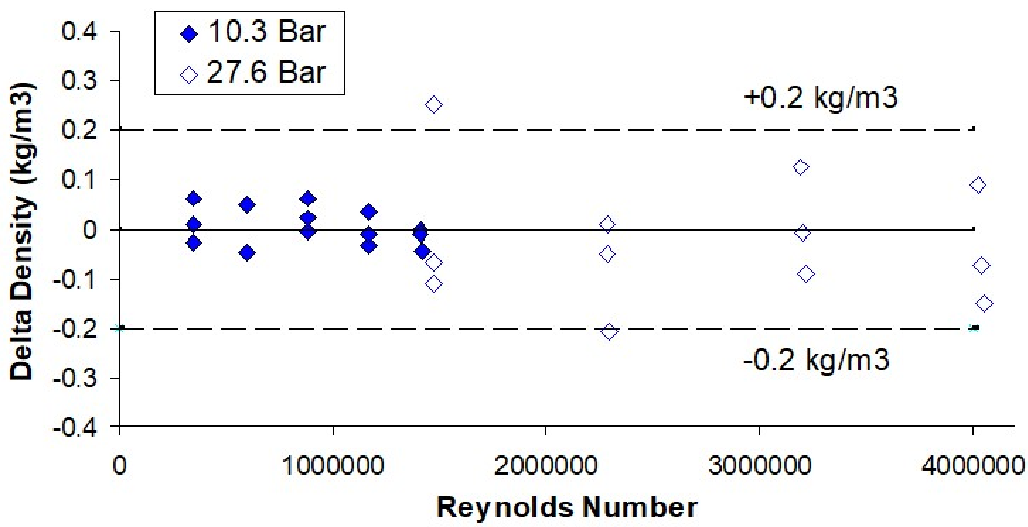

Figure 9. 3", 0.68β VorCone Meter Density Prediction Performance.

Figure 10. 6" to 4", 0.75β VorCone Meter at the CEESI Natural gas Facility.

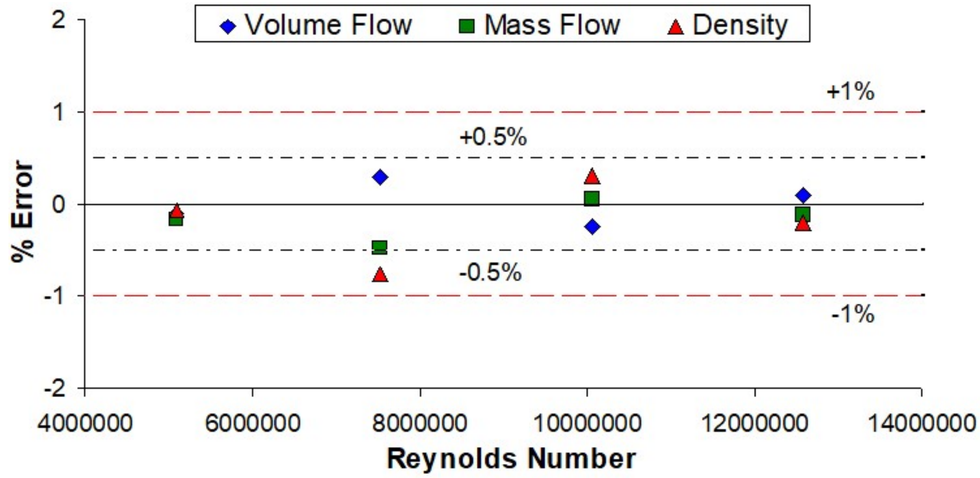

Figure 11. 4", 0.75β VorCone Meter Mass, Volume, and Density Results.

Figure 7 shows a 3", 0.68β VorCone meter under air flow calibration. The vortex meter velcoity vs. K-factor, and the cone meter Reynolds number vs. discharge coefficient, were each data fitted using the standard industrial method of a First Degree Spline Fit (commonly known as 'Piecewise Linear Interpolation', or simply a 'look up table'). The calibration data includes two pressures, 27.6 and 10.3 Bar. Figure 8 shows the volume flowrate, mass flowrate, and density uncertainty of 0.3%, 0.5%, and 1% respectively. Some mass meters have their gas density uncertainty stated in terms of ±ρ kg/m^3. Figure 9 shows this VorCone meter's gas density uncertainty is ±0.2 kg/m^3.

Figure 10 shows a 6" to 4" reduced bore 4", 0.75β VorCone meter at the CEESI wet natural gas facility. This meter was tested with single phase natural gas flow at 50 Bar before wet gas tests. A linear fit was used to calibrate the vortex meter. A polynomial was used to calibrate the cone meter. The single phase data is at 40 Bar. Figure 11 shows the VorCone meter volume flowrate, mass flowrate, and density uncertainty is again 0.3%, 0.5%, and 1% respectively.

6.2 Example of Hybrid Mass Meter Used for It's Intended Purpose

Fig 12. Oil Truck with 4" VorCone Meters Installed.

Figures 12 and 13 show an oil truck with installed VorCone meters, and the said installed meters respectively. This is an example of this hybrid mass meter in a commercial operation. These are truck loading / unloading flow meters. With limited installation space, excessive vibration as the truck is on unpaved surfaces during transit, the meter operation involving flow stopping and starting, and varying oil grades, this is a challanging metering application. All flow meters used in this application tended to give significant scatter between batches. Figure 14 shows comparisons with the facility storage tank reference uncertainty of 0.5% error bars. Both loading and unload VorCone meters predicted the volume flow to 1% uncertainty. The scatter and volume flow uncertainty was

Fig 13. Oil Truck Mounted 4" VorCone Meters (One per Flow Direction).

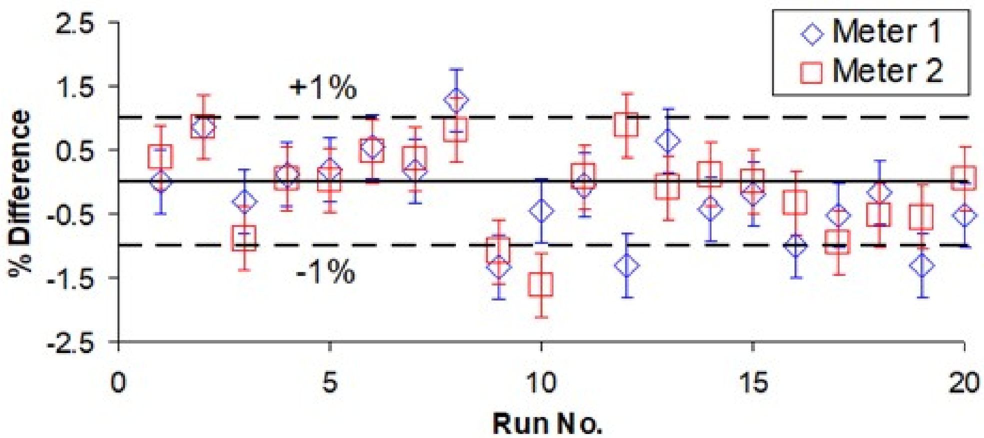

Fig 14. Truck 4" VorCone Meter Performances Compared to Facility Reference.

similar to Coriolis meters used on other trucks. However, as with Coriolis meters, the totalized oil quantity (volume) values for loading and unloading over twenty runs showed good agreement with the facility references. Table 1 shows the facility volume reference vs. the meters loading & unloading totalized values. The volume difference between the facility references and the loading and unloading meters are -0.19% and -0.09% respectively. Despite installation vibrations, no re-zeroing / re-calibration was required.

	Reference (Tank) BBLs	Meter Under Test BBLs	% Difference of Total
Meter 1 Loading	4488.8	4480.4	-0.19
Meter 2 Unloading	4488.8	4484.6	-0.09

Table 1. Totalized Flow Rate Results.

This truck flow metering application tends to use mass flow meters, but use them as volume flow meters. This is a throwback to measuring oil in volume (barrels). However, the density measurement was used. The oil usually contains some water the separates due to gravity. The ability to measure density allows the truck operators to know when the flow switches from oil to water.

6.2 Example of Hybrid Mass Meter NOT Used for It's Intended Purpose

An oil company installed VorCone meters in a saturated steam Enhance Oil Recovery (EOR) system. Injected saturated steam heats heavy oil, reducing its viscosity, making it easier to extract. Steam is expensive, with considerable fuel costs and boiler CAPEX and OPEX. There are application dependent optimum steam quality (i.e. heat injection) values. Too high a steam quality and a needlessly excessive amount of heat is injected while possibly causing fouling of the steam pipeline. Too low a steam quality and there is not enough heat injected to optimize the process. However, it is notoriously difficult to meter saturated steam quality – it's a two-phase flow metering problem.

Most modern traceable two-phase flow metering research has been carried out with ambient temperature natural gas and light oils and / or water. However, saturated steam has quite different fluid properties. Specifically, very hot water has a much lower surface tension than ambient temperature oil or water. Hence, unlike ambient temperature wet natural gas flows, horizontal saturated steam flow tends to flow as a mist even at moderate pressures and flow rates. That is, unlike wet natural gas flows, data shows that saturated steam can be reasonably modelled as a mist / pseudo-homogenous flow. The meter further helps mixing.

Steam quality, is defined by equation 5, where m_g and m_l denote the mass flow of steam (i.e. gas) and water (i.e. liquid) respectively. Using the homogenous model the vortex meter sub-system predicts the homogenous or 'total' volume flow ($Q_{V,Total}$), see equation 1a. The VorCone meter produces a homogenous fluid density prediction (ρ_{hom}), see equation 3a. For read pressure and temperature the steam tables state the saturated steam's water (ρ_l) and steam (ρ_g) densities. Hence, the steam quality can be derived from equation 6.

$$x = \frac{m_g}{m_g + m_l} \quad \text{-- (5)} \qquad\qquad Q_{v,Total} = f/K \quad \text{-- (1a)}$$

$$\rho_{\text{hom}} = 2\Delta P \left\{ \frac{C_d}{Q_{v,Total}} \frac{A\beta^2}{\sqrt{1-\beta^4}} \right\}^2 \quad \text{-- (3a)} \qquad\qquad x = \frac{\rho_g(\rho_l - \rho_{\text{hom}})}{\rho_{\text{hom}}(\rho_l - \rho_g)} \quad \text{-- (6)}$$

Figure 17 shows a 2", 0.5β VorCone meter at a heavy oil field saturated steam injection point. The operators temporarily installed a portable cyclone separator reference system. The valve settings where then varied to vary steam quality and check the meter. Figure 18 shows the field, the meter, and part of the reference system cyclone separator. Most saturated steam quality systems only operate above x > 80% and are approximate. Such is the difficultly of metering steam quality in the field, not least due to difficulty of guaranteeing full separation and the natural phase change with even slight thermodynamic condition changes, that even the field reference has an uncertainty of ≈5%. Figure 19 shows the predicted vs. reference steam quality with reference uncertainty bars. The VorCone meter tracked changes in steam quality, and gave quality predictions across a 40% ≤ x ≤ 100% range. Whereas steam quality is notoriously difficult to measure, the theoretical steam quality prediction is only marginally outside the reference error bars.

Cone meters are known to over-read the gas flow in wet gas flow applications. ISO TR 12748 [11] gives a two-phase flow cone meter correction factor, where for a given Lockhart Martinelli parameter (X_{LM}), the percentage gas flow over-reading is predicted. The Lockhart Martinelli parameter (X_{LM}) and quality (x) are alternative methods of quantifying liquid loading, i.e. the relative amounts of liquid to gas. Equation 7 shows the conversion from quality (x) to Lockhart Martinelli parameter (X_{LM}). Hence, with the steam tables stating the steam (ρ_g) and water (ρ_l) densities, and the quality (x) predicted, the VorCone meter also produces a Lockhart Martinelli parameter prediction (X_{LM}). The uncorrected ('apparent') steam mass flow ($m_{g,App}$) prediction from the cone DP meter sub-system is then predicted by applying the ISO cone meter correction (equation 8).

Figure 18 shows the uncorrected steam mass flow over-reading. In these saturated steam conditions the cone meter sub-system will over-read the steam vapour flow by up to 32% across . This is a typical response of standard single

Fig 15. 2”, 0.5β VorCone Meter Saturated Steam Meter at the Injection Point.

Fig 16. Saturated Steam Portable Cyclone Separator Reference System at Well Head.

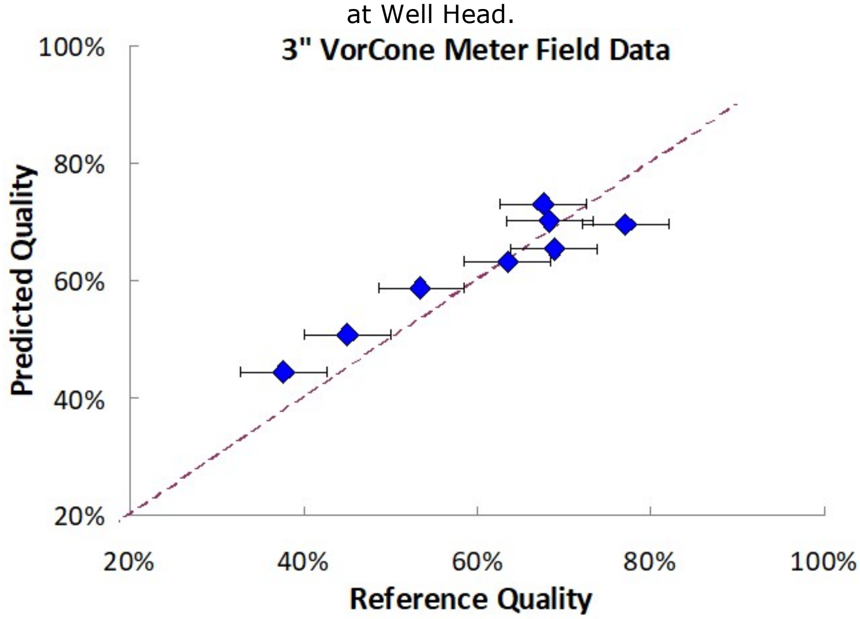

Figure 17. 2”, 0.5β VorCone Meter Saturated Steam Flow Quality Results.

$$X_{LM} = \frac{m_l}{m_g}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{1-x}{x}\sqrt{\frac{\rho_g}{\rho_l}} \quad \text{-- (7)}$$

$$m_g = \frac{m_{g,app}}{f(\rho_g, \rho_l, x, m_g)} \quad \text{-- (8)}$$

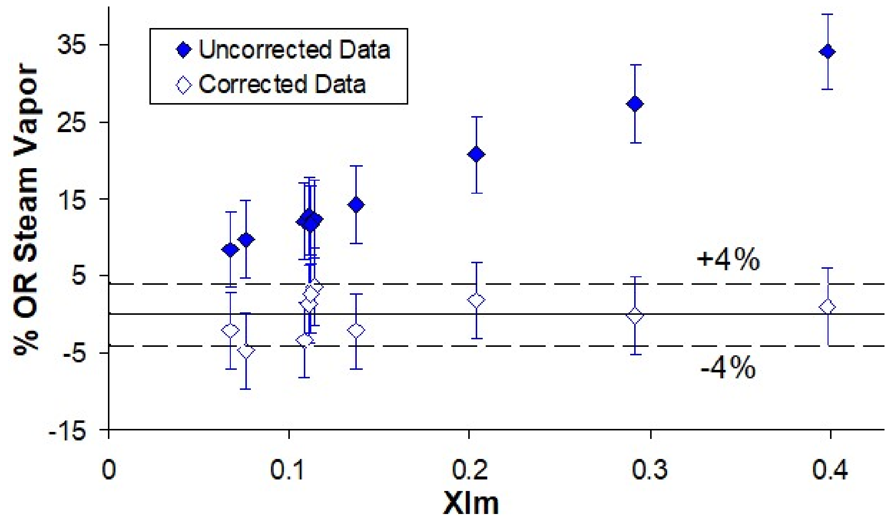

Figure 18. 2”, 0.5β VorCone Meter Saturated Steam Uncorrected and Corrected Steam Vapor Mass Flow Predictions.

phase flow meter in wet gas / saturated steam applications. Wet gas / saturated steam is an adverse flow condition for single phase flow meters. Applying the VorCone meter quality (or Lockhart Martinelli parameter) prediction to the ISO cone meter wet gas correction gives the saturated steam VorCone meter a steam flow prediction uncertainty similar to the reference system, i.e. 4% uncertainty.

Figure 19. 4”, 0.75β VorCone Meter Installed At Steam Boiler Outlet.

Figure 19 shows a 4”, 0.75β VorCone meter at a heavy oil field’s saturated steam boiler outlet. This saturated steam flow has multiple splits (of uncontrolled quality) downstream of this metering point as it flows to various injection point meters before injection. The boiler is set to produce approximately 72% quality steam. Previous to this VorCone meter installation the operators had to blindly trust the boiler setting, as no steam meter could check qualities < 80%. This VorCone meter read a quality of 73%.

7. A HYBRID HEAVY OIL FLOW METER CASE STUDY (EXAMPLE 2)

Heavy oil, i.e. API < 20°, is extremely viscous. With Reynolds numbers ranges often straddling the laminar / turbulent transition zone, it is notoriously difficult to meter. Most flow meter flow coefficients (or ‘MF’ meter factors) vary across this Reynolds number range. For example, in 2008 ConocoPhillips released Venturi meter data where a C_d almost halved in size over a $1e2 \le Re \le 1e5$ range (see

Figure 22). Whereas, not all flow meters are that sensitive to low range Reynolds numbers they are all somewhat sensitive. It is therefore important to know or derive a flow's Reynolds number as part of the metering process. However, the fluid properties of heavy oils significantly change with composition and temperature. The operator is often unsure of heavy oil fluid viscosity and density, and therefore the flow's Reynolds number is unknown. As such, various researchers have looked at hybrid meters designs to solve this problem.

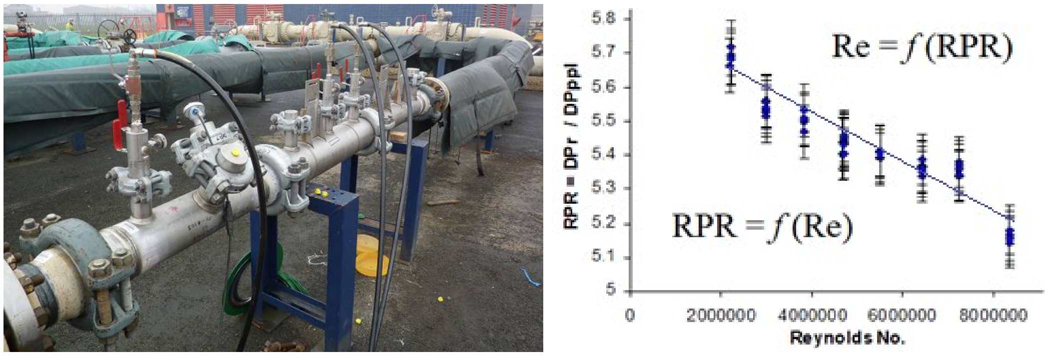

Figure 20. 6", 0.4β Venturi Meter at GLIS, and RPR vs. Reynolds No. Relationship.

In 2011 Vijay et al [12] showed that a Venturi meter with the DP Diagnostics diagnostic system 'Prognosis' (see Figure 20) had multiple parameters sensitive to the Reynolds number. Prognosis uses the DP readings as shown in Figure 5. Figure 20 shows the 6", 0.4β Venturi meter with Prognosis being calibrated with natural gas flow at GLIS. Note the 3rd pressure tap in the foreground as shown in Figure 5. Figure 20 reproduces the Prognosis parameter 'Recovered to Permanent Pressure Loss' ('RPR') vs. Reynolds number data. The Reynolds number can be approximated from known (readable) DP ratios.

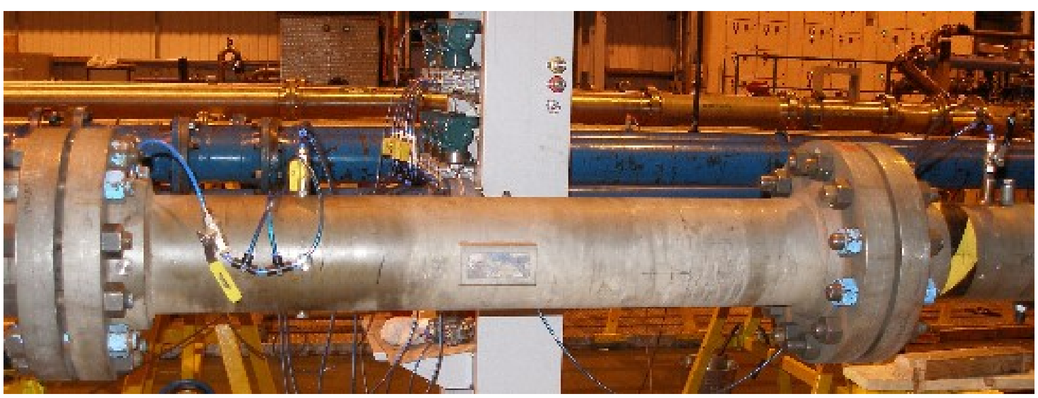
Figure 21. 8" Venturi Meter with Prognosis DPs at TUVNEL Heavy Oil Facility.

In 2012 TUVNEL tested heavy oil flow Venturi meters with the 3 DPs required by Prognosis, see Figure 21. In 2014 Rabone et al [13] showed the Prognosis results for this meter. Figure 22 includes this meter's C_d vs. Re data. Rabone et al showed the DP Ratio vs. Reynolds number relationships, see Figure 23. For a limited Reynolds number range the Prognosis DP Ratio checks were sensitive to the Reynolds number, thereby allowing the Reynolds number to be found. In turn this allowed the discharge coefficient to be found via a C_d = f(Re) data fit. However, there is a clear limitation.

Figure 23 shows the very significant limitation of the Venturi meter DP Ratios to predicting the Reynolds number. By a Reynolds number of approximately 600 onwards the DP Ratio relationship with Reynolds number begins to dissipate. And at approximately 1,200 Reynolds number there are step jumps in the DP Ratios

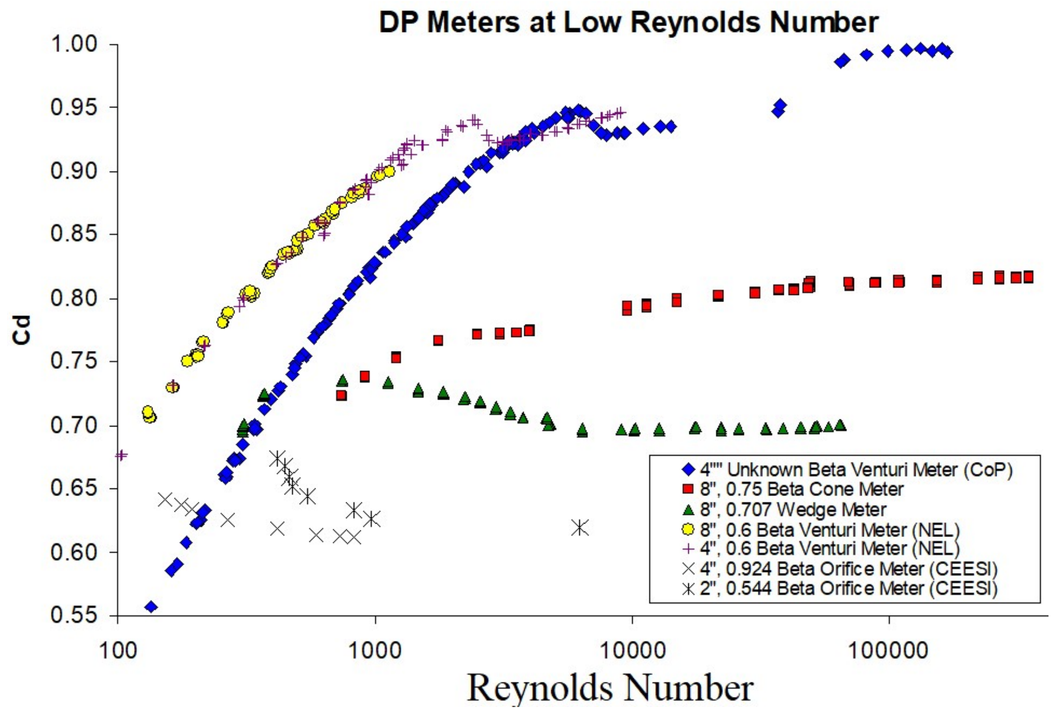

Figure 22. Multiple DP Meter Heavy Oil / Low Reynolds Number C_d vs Re Data.

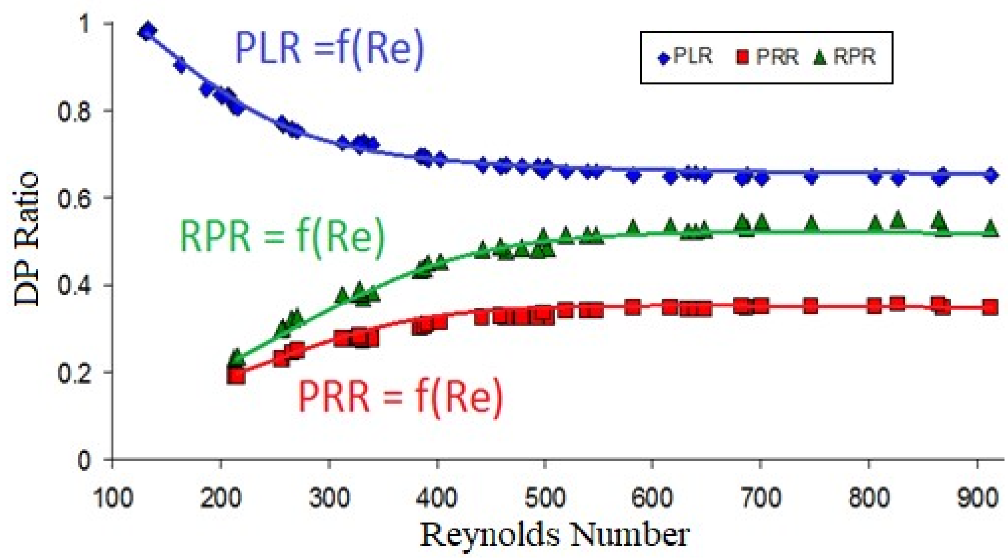

Figure 23. TUVNEL 8”, 0.6β Venturi Meter DP Ratios vs Reynolds Number.

(not shown here, see Rabone [13]). Industry needs a DP meter design with smoother, more distinct, more ‘fittable’ DP Ratio vs. Reynolds Number relatiosnships over a wide Reynold number range. And they exist.

In 2015/16 CEESI commissioned a heavy oil flow facility. The primary reference was a ball prover, and the secondary reference was a bank of 8” helical turbine meters. During this facilities commissioning in order to achieve marketing material the then CEESI management worked with DP Diagnostics to log Prognosis data on 8” cone (Figure 24) and wedge (Figure 25) meters. Only one reference turbine meter was required in these tests. The meter under test and turbine meter were in series, although the former was on the outbound leg and the latter on the return leg. The reference turbine meter can be seen in Figures 24 and 25. With steady incompressible flow the outputs of the reference turbine meter and meter under test are directly comparable.

In 2016 Steven and Cousins [14], and in 2017 Steven [15], presented Figure 22 including the cone and wedge meter C_d vs. Re data sets. In both papers it was stated that Prognosis (i.e. DP meter pressure field analysis) could be set to predict the Reynolds number and fluid viscosity.

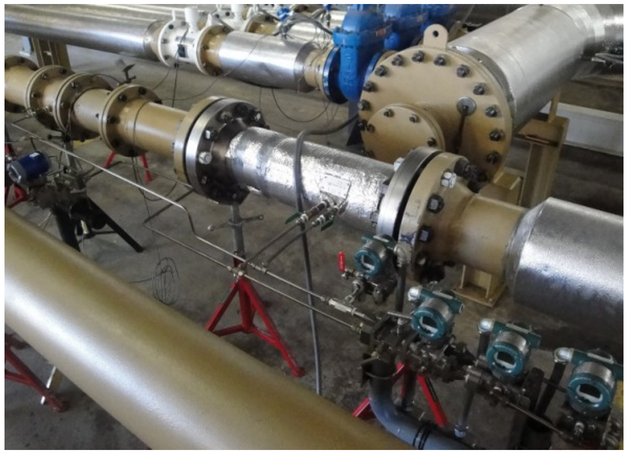

Figure 24. 8” Cone Meter with Prognosis in Series with an 8” Helical Turbine Meter in CEESI’s Heavy Oil Facility.

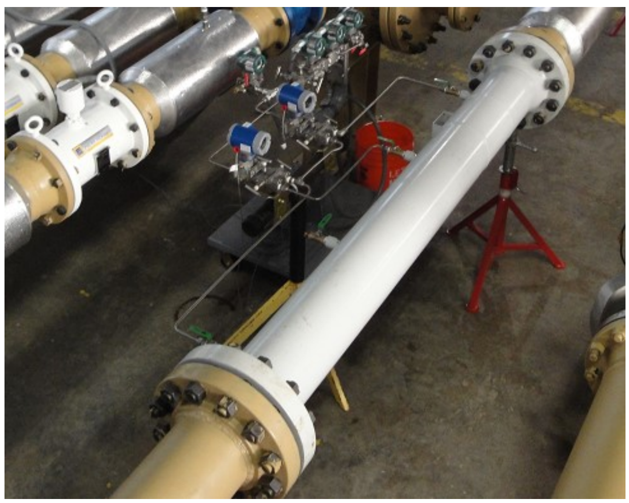

Figure 25. 8” Wedge Meter with Prognosis in Series with an 8” Helical Turbine Meter in CEESI’s Heavy Oil Facility.

The cone and wedge DP meters tested had a superior heavy oil performance to the Venturi meters. Figure 22 shows that the tested cone and wedge meter C_d values vary less across the low Reynolds number range than that of Venturi meters. For 5e2 <Re< 1e5 the cone meter C_d drops by 10%, the wedge meter C_d varies by 6%, while the Venturi meter C_d drops by >25%. For a metering system where the Reynolds number is to be estimated with some stated uncertainty, the less sensitive (or volatile) the C_d is to Reynolds number the better.

Figure 26 and 27 also show the CEESI 8” cone and wedge meter DP Ratios vs. Reynolds numbers data cited by Steven et al [14]. Both the wedge and cone meters have useful DP Ratio vs Reynolds number relationships. Specifically, for the heavy oil Re<2e5 range, the wedge and cone DP meter RPR readings have very clear, smooth, and ‘data fittable’ relationships with Reynolds number, with none of the Venturi meter flatness or discontinuities.

The DP meter isn’t the only flow meter that has a sensitivity to Reynolds numbers at the low Reynolds number range. Most do. Figures 28, 29, and 30 show CEESI 8” helical turbine meter, blinded Coriolis meter, and blinded ultrasonic meter

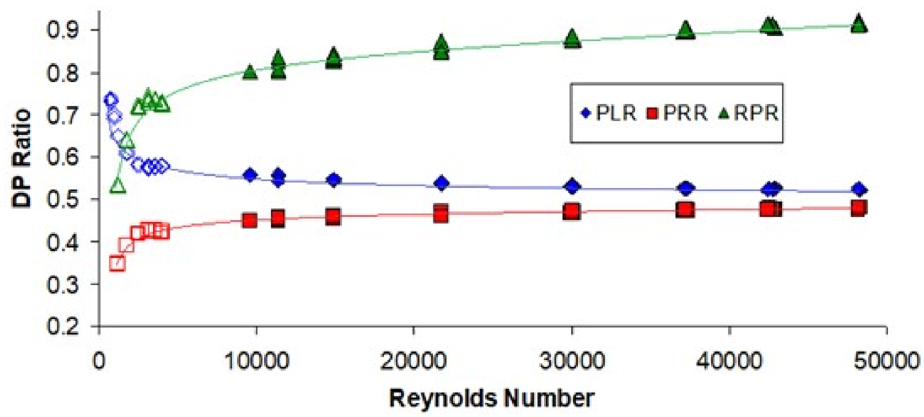

Figure 26. 8”, 0.75β Cone Meter Prognosis DP Ratios vs. Reynolds Number.

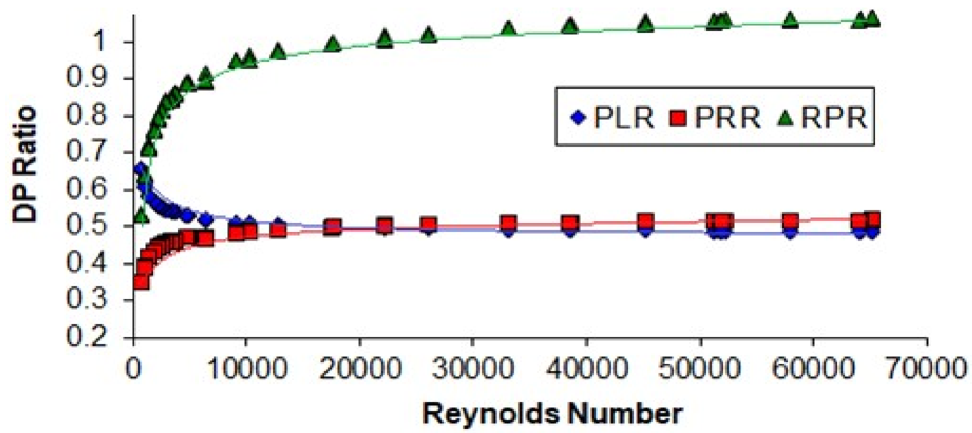

Figure 27. 8”, 0.707β Wedge Meter Prognosis DP Ratios vs. Reynolds Number.

heavy oil data sets respectively (as shown by Steven [15]). Below about 10,000 Reynolds number all these flow meters begin to exhibit a significant Reynolds number sensitivity that is not present at higher Reynolds number values. The Coriolis and ultrasonic meter graphs include the conventional approximation of the laminar / turbulent transition zone (green lines) and the reality of this transition being unpredictable occurring at different Reynolds numbers (red line).

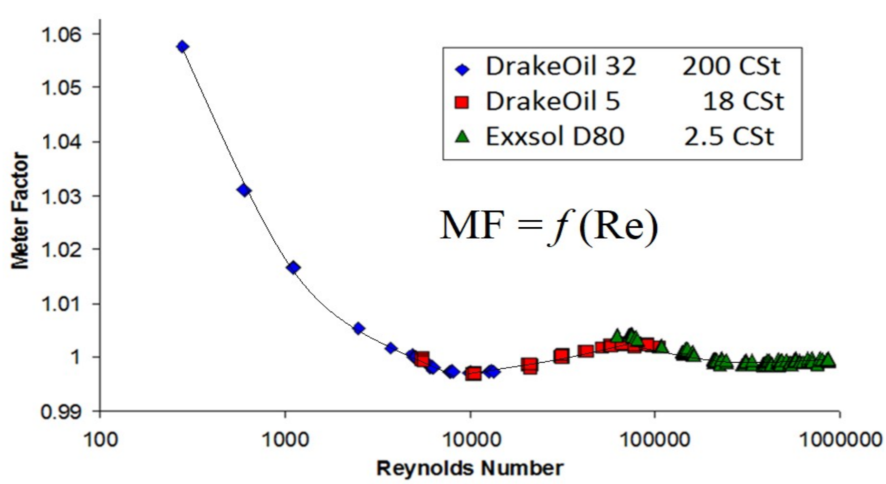

Figure 28. CEESI 8” Helical Turbine Meter Calibration Curve.

Noting the different data ranges of the respective graphs in Figures 28, 29, and 30, we see that across the communal 2e3 ≤Re≤ 1e6 range the helical turbine meter’s MF changes by ≈ 1.5%, the Coriolis meter by ≈ 0.8%, and the ultrasonic

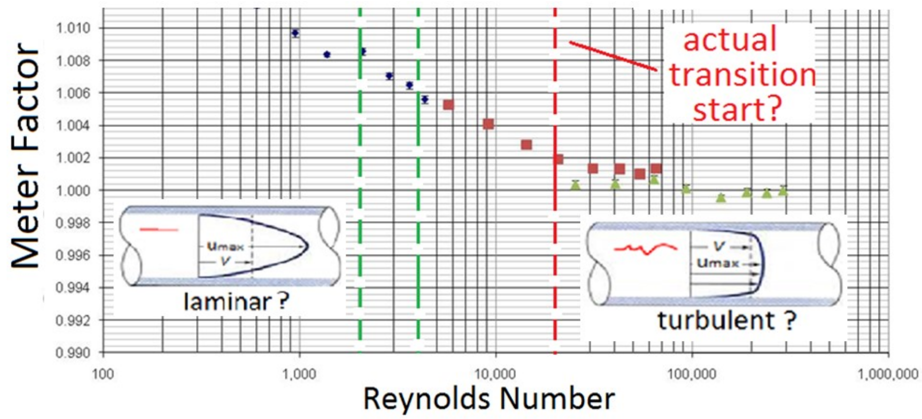

Figure 29. Blinded Coriolis Meter Heavy Oil MF vs. Reynolds No. Data.

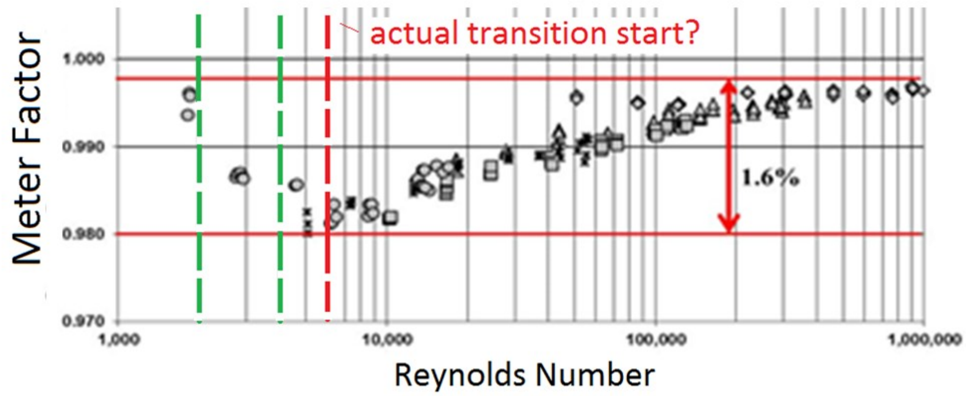

Figure 30. Blinded 4" Ultrasonic Meter Heavy Oil MF vs. Reynolds No. Data.

meter by ≈ 1.6%. However, the lower the Reynolds number the bigger the issue, e.g. extending the range to 1e3 ≤ Re ≤ 1e6 increased the helical turbine meter MF shift to 6%. Hence, even for these flow meter types, knowing the Reynolds number to instigate a MF correction is very beneficial. But as stand-alone flow meter devices they have no known way of estimating the Reynolds number.

Figures 22, 28, 29, and 30 show that the helical turbine, Coriolis, and ultrasonic meter factors tend to have less sensitivity to the low Reynolds number than DP meters. However, whereas compared to other meters types, the DP meter may have a relatively high meter factor (i.e. C_d) variance across the heavy oil Reynolds number range, unllike other meters[3] it has a solution, i.e. the Prognosis DP Ratios prediction of Reynolds number and associated C_d correction. However, it's arguable that a DP meter's higher sensitivity to Reynolds number means that a C_d=f(Re) fit will have a higher uncertainty than other flow meter MF = f(Re) fits. Therefore, one solution is a ***hybrid*** meter, i.e. use the DP meter as a Reynolds number meter, and then input that Reynolds number prediction into a dissimialr meter with lower Reynolds number vs. meter factor sensitivity. This could be two independent meters in series forming one heavy oil flow metering system, or some form of a true hybrid meter design.

As way of example, let us look at the wedge meter coupled with the helical turbine meter (see Figure 25). This data is in reality a calibration data set where the helical turbine meter is the reference meter used to calibrated the wedge meter. But the data allows an example where the principle can be discussed. The Reynolds number is predicted by the wedge meter Re=f(RPR) relationship.

[3] Some Coriolis meters have inbuilt viscosity measurement capability, but this is generally approximate, and the authors have not seen any such heavy oil data.

The volume flowrate is predicted by inputting this Reynolds number into the helical turbine meter's MF=f(Re) data fit. And, as the two meters are wedge (density sensitive) and a turbine (density insensitive) volume flow meters in series, we can apply the Boden concept to also predict fluid density, mass flow and viscosity. Figure 31 shows a flow chart of the wedge and turbine combined metering system.

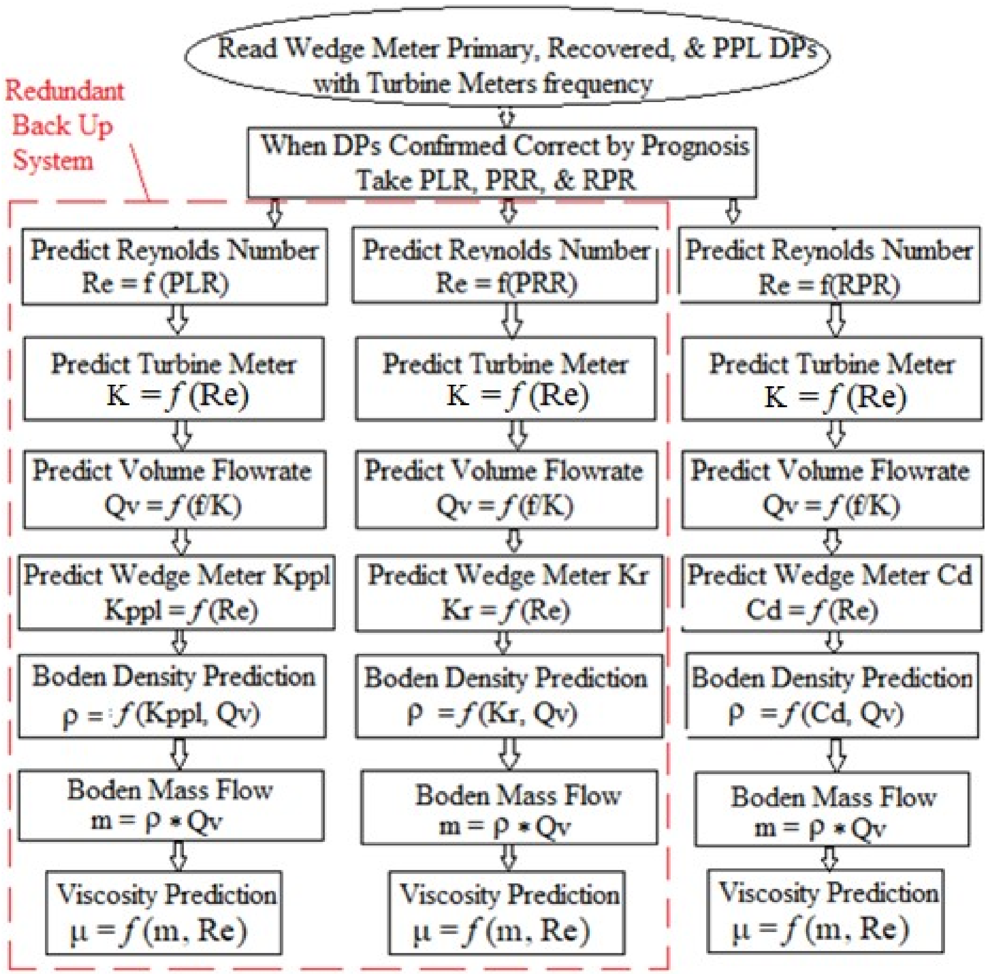

Figure 31. Wedge /Helical Turbine Meter Heavy Oil Meter Operational Flow Chart.

Figure 32 shows the algorithm in graphical form. The reference conditions are 72.85 kg/s, a volume flow of 301.2 m^3/hr, fluid density of 870.76 kg/m^3 and a reynolds number of 2558. The wedge meter read a PLR of 0.552, a PRR of 0.447, and a RPR of 0.810. Then Re =f(RPR) estimated Reynolds number was 2481 (-3%). Then, turbine meter Meter Factor was derived, MF = f(Re), as 1.004 with a resulting turbine meter volume flow prediction of 300.4 m^3/hr (-0.27%). The wedge meter discharge coefficient was derived, C_d = f(Re), as 0.72 (+0.3%). The resulting Boden density prediction is 877.5 kg/m^3 (+0.8%), and the Boden mass flow prediction is 73.2 kg/s (+0.5%). When the Reynolds number is directly predicted, there is no practical necessity to then know the fluid viscosity. However, a viscosity prediction is a by-product of the calculation. The reference viscosity was 0.186 Pa.s, whereas the method predicted 0.194 Pa.s (+4.4%).

Figure 31 includes the alternative of using the other two Prognosis DP Ratio and DP meter flowrate algorithms. The details of these DP meter calculations can be found in Rabone [13]. This shows double redundancy on the DP part of the hybrid meter. Unfortunately, the turbine meter has no redundancy. This is common in hybrid meter designs, not every system is duplicated to create redundancy. Nevertheless, using the Prognosis secondary expansion and PPL DP flow algorithms each with the helical turbine meter produced parrallel calculaions.

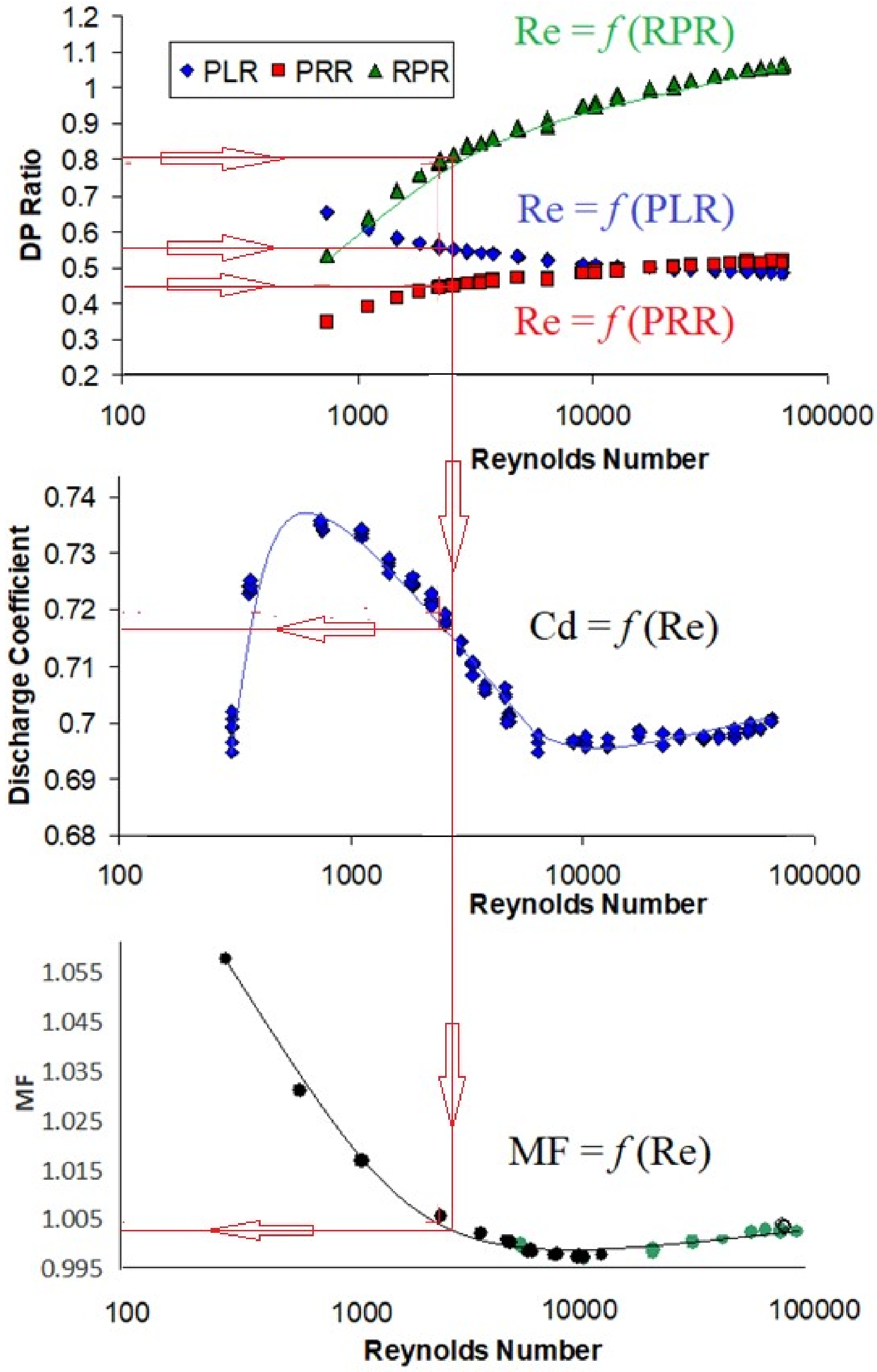

Figure 32. Combined Wedge / Helical Turbine Meter Heavy Oil Meter Example.

Finally, in 2017/2018 Marshall [16, 2] described, with a twist, a similar hybrid meter design. Figure 33 reproduces a Marshall [2] hybrid meter set up. Instead of using a conventional DP meter with Prognosis DP Ratios to derive Reynolds number, Marshall used a spool piece 'permanent pressure loss' meter.

Marshall cited the hydraulic permanent pressure loss (ΔP_{PPL}) equation for flow through a length of pipe, i.e. Equation 9, where ΔP_{PPL} is the pressure drop across pipe of length 'L', inside diameter 'D', friction factor of 'λ', density 'ρ' , and average flow velocity 'V'. Converting this equation into an expression of volume

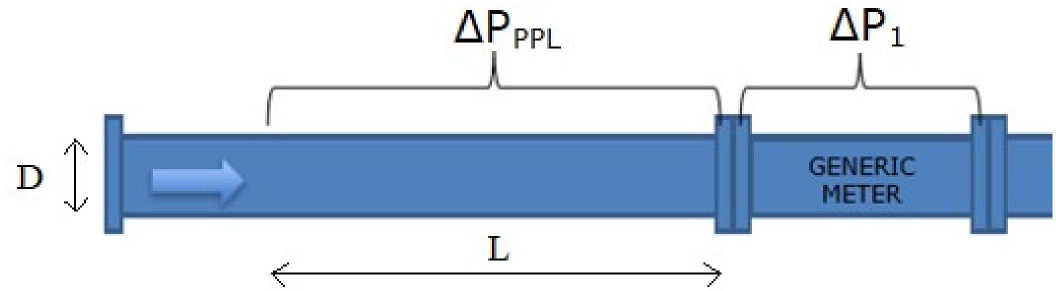

Figure 33. Marshall [2] Spool with Generic Meter Heavy Oil Metering System.

flowrate Q_V, where for inlet area 'A', Q_V=AV, gives Equation[4] 10. When this spool piece meter is upstream of a generic DP meter with DP signal ΔP_1, equating the DP meter and 'spool' meter volume flowrate expressions gives Equation 11, and reducing / rearranging gives Equation 11a.

$$\Delta P_{PPL} = \lambda \frac{L}{D}\left(\frac{\rho V^2}{2}\right) \quad \text{-- (9)} \qquad Q_V = A\sqrt{\frac{D}{L\lambda}}\sqrt{\frac{2\Delta P_{PPL}}{\rho}} = AK_{PPL}\sqrt{\frac{2\Delta P_{PPL}}{\rho}} \quad \text{-- (10)}$$

$$Q_V = \frac{A\beta^2}{\sqrt{1-\beta^4}}C_d\sqrt{\frac{2\Delta P_1}{\rho}} = A\sqrt{\frac{D}{L\lambda}}\sqrt{\frac{2\Delta P_{PPL}}{\rho}} \quad \text{-- (11)}$$

$$C_d\sqrt{\lambda} = f(\mathrm{Re}) = \frac{\sqrt{1-\beta^4}}{\beta^2}\sqrt{\frac{D}{L}}\sqrt{\frac{\Delta P_{PPL}}{\Delta P_1}} \quad \text{-- (11a)}$$

A DP meter's discharge coefficient is a function of Reynolds number, C_d =f(Re). The specific function is meter specific, but it is known from standards or calibration. A spool piece's friction factor is also a function of Reynolds number, λ = f(Re). The function is effectively the Moody diagram plot, often expressed as Colebrook's function. Hence, equation 11a has one unknown, the Reynolds number found by iteration. From here Marshall's method is as described above, inclusive of again introducing the Boden method by optionally adding an independent volume meter to the hybrid system to find density.

Designers of such a system would have to cognizant of the hybrid meter design rules. The 'spool' piece meter would need to be 'sized' such that the ΔP_{PPL} range across the flow range was large enough to be readable to an acceptable uncertainty (i.e. Rule 1). This relates to the flow range compatibility of the spool and generic flow meters in series (i.e. Rule 2). For a given pipe diameter 'spool' meter sizing becomes specifying the spool meter length (or relative roughness!). The spool meter length may need to be substantial, or a special low range DP transmitter may need to be used. Also, the Colebrook equation requires a pipe relative roughness. It may be necessary to calibrate such a meter, and somehow monitor for changes in relative roughness. A more compact design is to dispense of the spool and read the higher ΔP_{PPL} across a DP meter as described above.

Nevertheless, the authors appreciate all such hybrid meter research. The general hybrid meter design principles of these various researchers could and arguably should be developed into commonplace methodolgies to help solve the persistent problem of heavy oil / low Reynolds number flow metering.

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[4] This is the flowrate expression *specifically* for a length of straight pipe with a stated ΔP_{PPL}. The DP meter 'Prognosis' system uses this expression's *general* form for PPL across *any* pipe component, with a DP meter's PPL flow coefficient 'K_{PPL}' used (Rabone [13]). In this specific case of a straight pipe, $K_{PPL} = \sqrt{D/L\lambda}$.

8. A HYBRID FLOW METER DIAGNOSTIC SYSTEM (EXAMPLE 3)

Several flow meter types have verification systems powered by diagnostic suites. The diagnostic methodology of different flow meter types are naturally based on the specific physical principles utilsed by that meter type. However, not all flow meter type diagnostic suites are equal. Some meter types have more powerful, sophisticated, and useful diagnostics than others. Nevertheless, each meter type diagnostic system offers different, sometimes unique, information about the condition of a flow meter and the flow. Hence, as there is benefit in cross-referencing different primary meter types, there is benefit in cross-referencing different meter type diagnostics systems. For a hybrid meter, even if one meter type has a more capable diagnostic system than the other, the principle is that each diagnostic system contains unique information, and even if one diagnostic system contains less informative, this information is *additional* information and therefore worthy of cross-referencing.

A significant issue with hybrid meter design is the challenge of the interoperability of the different metering systems. This issue is particularly challanging when considering an individual flow meter diagnostics's software ability to exchange information with another flow meter type's diagnostics's software and make sense of very different forms of information. A relatively simple approach is to take each meter type's diagnostic system and convert it's outputs to a standard diagnostic display template. By coding each flow meter's common malfunction's diagnostic patterns as identification markers, the software can create a short list of issues that cause such pattern on that flow meter. In the case of a hybrid meter the two (or more) metering sub-systems will have independent lists. Cross referencing these lists will give more resolution to the source of the problem.

8.1 **Flow Meter Diagnostic Suite Displays**

Flow meter diagnostic suite displays are the flow meter user's window into the internal meter's world of flow conditions, adverse events, and system failure. However, the typical flow meter user operates various process equipment and is not a flow meter specialist. As flow meter diagnostic systems grows in capability and complexity, some flow meter diagnostic displays can give the non-specialist flow meter user cognitive overload. To many uninitiated users flow meter diagnostic displays can appear incomprehensible. Flow meter manufacturers should ask themselves who their diagnostic displays are actually for, the few experts for rare post analysis, or average non-specialist users for common periodic live checking? If the user cannot understand the message, the message cannot be part of the operational and maintenance philosophy. Simple, clear diagnostic dispalys are therefore arguably beneficial.

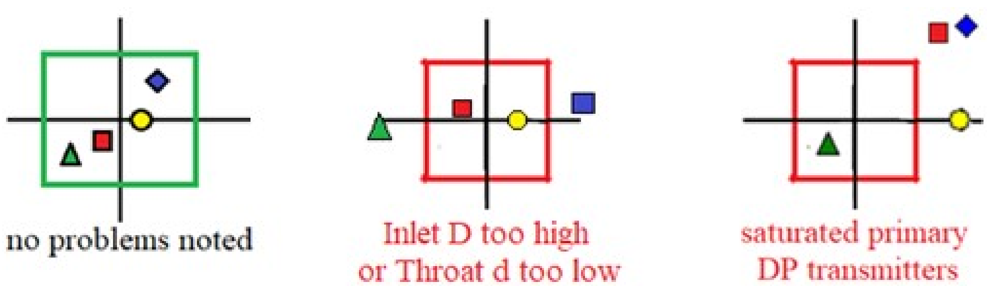

Figure 34. Examples of Venturi DP Meter Prognosis Results.

These authors believe that flow meter diagnostic suite visual displays should provide the flow meter user a *clear* indication of operational equipment and flow conditions commensurate with the flow meter operational and maintenance philosophy. As such, the comprehensive DP meter diagnostic system 'Prognosis' was developed to have a simple display that gives the user a clear message.

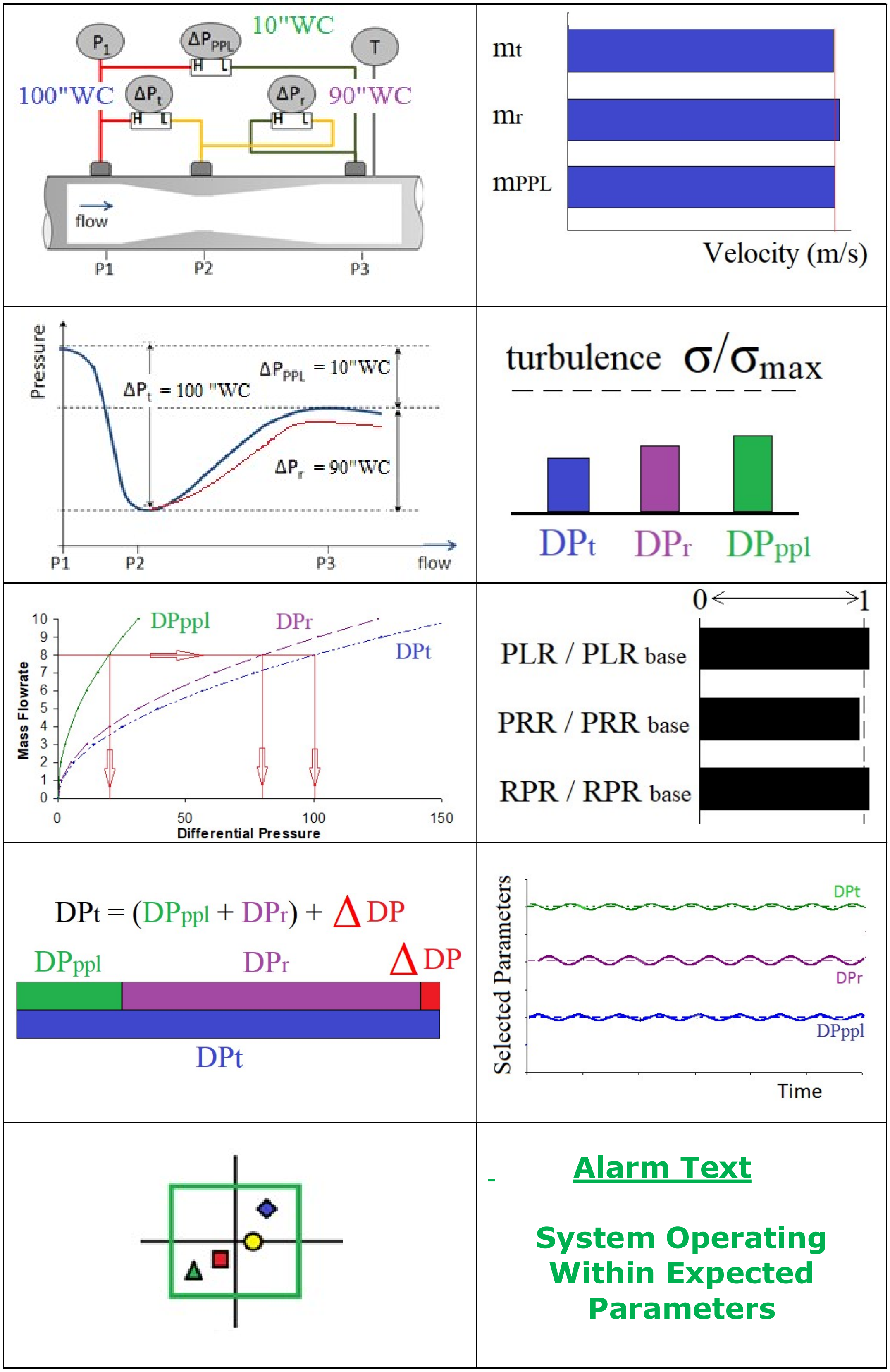

Figure 35. Example of a Comprehensive DP Meter (Prognosis) Diagnostic Display.

'Prognosis' has been discussed in various events over the last few years (e.g. Vijay [12]). With a mechanical set up shown in Figure 5 the diagnostics are plotted on a simple graph where the points inside the box means no problem, and one or more points outside the box means a possible meter malfunction. When point/s are outside the box, pattern recognition software either states a specific problem, or short lists potential problems. Figure 34 shows Venturi DP meter Prognosis examples.

Nevertheles. although the average user with limited training could be offered a more user friendly simple front screen display this doesn't exclude the use of more comprehensive complex displays. Once a simple front screen engages the user and indicates a problem exists, moe complex displays would then be valuable to subject matter specialists for further analysis. In fact, some knowledgable users complain that the DP meter Prognosis display (Figure 34) is ***too*** simplified, with subtle details found by the diagnostic system not included in the display. All flow meter diagnostic systems could have a simple front screen for non-specialist users, and a more comprehensive secondary display for subject matter experts. Figure 35 shows an example of a more comprehensive secondary display for subject matter experts using DP meter diagnostics (i.e. 'Prognosis').

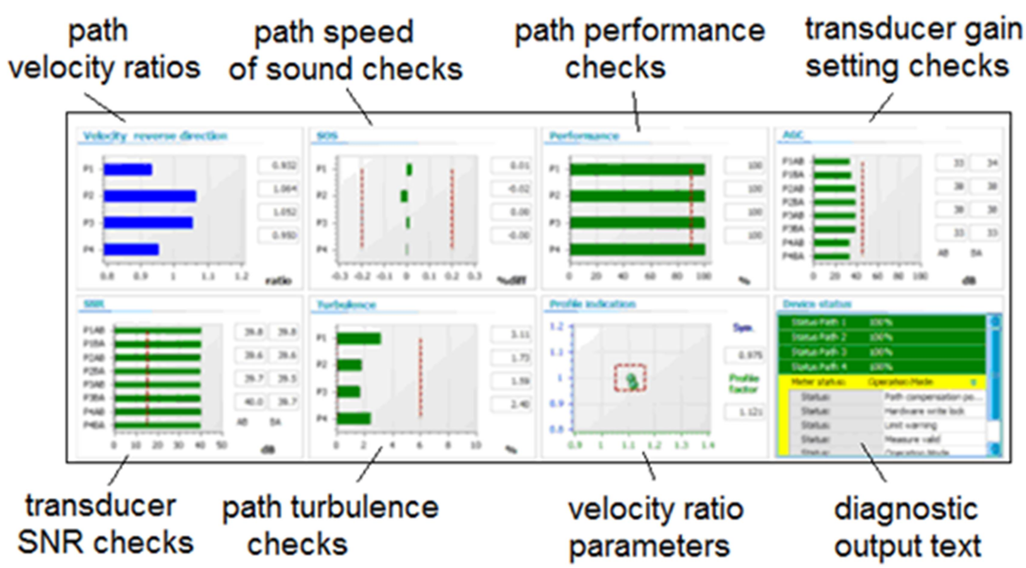

Figure 36 Example of Ultrasonic Meter Dignostic Display.

Ultrasonic meter diagnostic displays have the opposite issue to DP meter diagnostic displays. The high quality ultrasonic meter diagnostic system is displayed in relatively comprehensive complex displays only. There is no simplified front screen for the non specialist user. Different ultrasonic meter manufacturers use the same diagnostic physical principles, containing the same multiple parameter checks. However, manufacturers vary on how to display the results. Figure 36 shows an ultrasonic flow meter diagnostic display example. This is a relatively compact display, some manufacturers choose to use multiple screens. Relatively few ultrasonic meter users can decypher the subtle details. Ultrasonic meter pattern recognition techniques tend to be left to the experience of the individual users, and not included in software and automated outputs. A simpler front display could be beneficial. An example is proposed here.

There are various ultrasonic meter diagnosti checks. Some are reproduced for every individual traansducer or path. For a simple first display to the regular user the display need only show the worst case scenario for each individual check type. If this worst case is acceptable then there is no need overload the user by showing every other results. The extra data offers no more useful information.

As an example, let us consider a chordal four path transient time ultrasonic meter (Figure 37). Each path (P1 to P4) reads the average flow velocity (V) and local

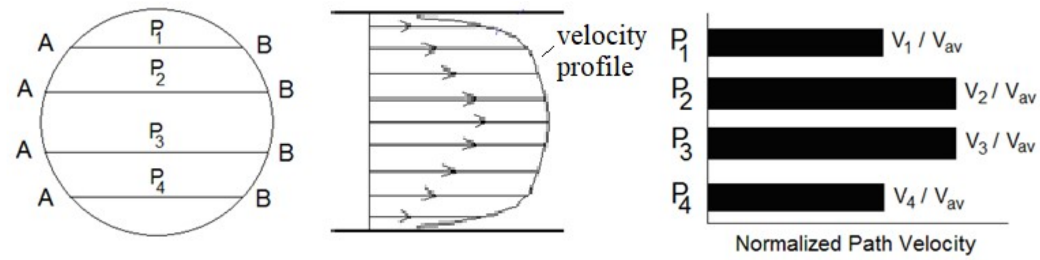

Figure 37. Four Path Generic Ultrasonic Meter, Actual Measured Velocity Profile.

speed of sound (c). For the first check, take the widest spread between the four path SOS measurements (i.e. $c_{i,max} - c_{i,min}$), and divide this by the allowable SOS spread limit, Δc_{lim} (usually 0.5 m/s). Equation 12 shows the plottable diagnostic value (x_1). Correct operation is now indicated by $0 \le x_1 \le +1$. A second check is to compare the average path speed of sound (c_{av}) with an external SOS prediction (c_{ext}). The maximum allowable difference (a%) is usually set at 0.2%. Equation 13 shows the plottable diagnostic value (y_1). Correct operation is now indicated by $-1 \le y_1 \le +1$. The speed of sound diagnostic checks can therefore be plotted as (x_1,y_1). If the point is inside a 1x1 box there is no speed of sound problem noted.

$$x_1 = \frac{c_{i,\max} - c_{i,\min}}{\Delta c_{\lim}} = \frac{\Delta c_{spread}}{\Delta c_{\lim}} \quad \text{-- (12)}$$

$$y_1 = \left\{ \left(\frac{c_{av}}{c_{ext}} - 1 \right) * 100\% \right\} / a\% \quad \text{-- (13)}$$

$$S = \frac{V_1 + V_2}{V_3 + V_4} \quad \text{-- (14)}$$

$$PF = \frac{V_2 + V_3}{V_1 + V_4} \quad \text{-- (15)}$$

$$\xi\% = \{(S_s / S_c) - 1\} * 100\% \quad \text{-- (16)}$$

$$\delta\% = \{(PF_s / PF_c) - 1\} * 100\% \quad \text{-- (17)}$$

A fully developed flow has a predictable and symmetrical flow profile (see Figure 37). Ultrasonic meter diagnostics check flow profile symmetry (S) by equation 14, and the flow profile shape, or 'profile factor' (PF), by equation 15. These parameters are theoretically known, but precisely found by calibration. Let *ξ%* (equation 16) represent the percentage difference in symmetry between service (S_s) and calibration (S_c). Let *δ%* (equation 17) represent the percentage difference in profile factor between service (PF_s) and calibration (PF_c). Letting the allowable symmetry and profile factor variations be b% and c% respectively, the profile checks become $x_2 = \xi\%/b\%$ and $y_2 = \delta\%/c\%$. Correct operation is now indicated by $-1 \le x_2 \le +1$ and $-1 \le y_2 \le +1$. The check can be plotted as (x_2,y_2), where inside a 1x1 box there is no profile problem noted.

Ultrasonic meters check both the Signal to Noise Ratio (SNR) and Gain on every transducer. Again, a basic display need only show the worst case scenarios. Unlike the SoS and profile checks these checks have subjective baselines, but baseline thresholds are set. A transducer's SNR check is for the actual (SNR_a) to be greater than this minimum allowed baseline threshold (SNR_b). For correct operation the result will be $SNR_a - SNR_b > 0$. This doesn't lend itself to a simple graph plot, but it can be forced: If the result complies set x_3 to zero, if not set x_3 to two. Next, consider the largest ratio of in-service (μ_s) to maximum (μ_{max}) transducer gain. Correct operation produces a $0 < \mu_s/\mu_{max} < +1$ result. Hence, let x_3 be the SNR check result of 0 or 2, and $y_3 = \mu_s/\mu_{max}$. These checks can be plotted as (x_3,y_3), where inside a 1x1 box there is no issues noted.

Ultrasonic meter diagnostics check path performance and path velocity prediction standard deviation (aka 'turbulence'). Path performance (ψ%) is the percentage of 'velocity' (i.e. Δt / path length) readings attempted over a period of time that were successfully read. Setting a minimum threshold for acceptable path performance (ψ_{min}%) gives the diagnostic parameter $\eta = (100\%-\psi\%)/(100\%-\psi_{min}\%)$. If $\psi\% \geq \psi_{min}\%$ then $0 \leq \eta \leq +1$, and all is well. If $\psi\% < \psi_{min}\%$, then $\eta > +1$. Let $x_4 = \eta$. Next, let $\omega\%$ be the percentage variation of a paths read flow 'velocity' readings over a set period of time. Let that path's maximum allowable percentage variation of gas 'velocity' (or Δt) be $d\%$. Hence, let y_4 be the highest value path turbulence result, i.e. $y_4 = \omega\%/d\%$. The checks are now $0 \leq x_4 \leq +1$ and $0 \leq y_4 \leq +1$, and the check can be plotted as (x_4,y_4), where inside a 1x1 box there is no issues noted.

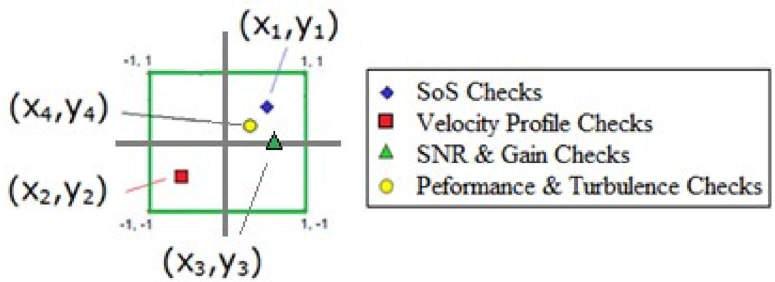

Figure 38. Example Simple Generic Ultrasonic Meter Diagnostic Front Display.

Figure 38 shows this examples resulting simple diagnostic display. This plot of only four points on a 1x1 box contains the summarized information in say Figure 36. To the uninitiated this display clearly says 'points in box good / out of box bad'. Pattern recognition should also lead to text appearing with points out the box stating the specific problem, or a short list of potential problems. Furthermore, points out the box can then lead to experts then examining the more detailed traditional diagnostics screens (e.g. Figure 36). In short, a simple display like Figure 38 is more accessible to the average non-specialist meter user and encourages the use of ultrasonic meter diagnostics.

In this example the authors reduced the ultrasonic meter diagnostic suite display to the same style as DP meter's Prognosis. Now in the case of hybrid ultrasonic / DP meters there would be two sets of plots, and two sets of pattern recognitions to cross-reference. As way of an example let us look at paired ultrasonic and Venturi meter examples. These meters could be in series, or the ultrasonic meter could be in the Venturi meter throat.

8.1 Example 1: Disturbed / Asymmetrical Flow

Disturbed flow (i.e. a distorted velocity profile) cause ultrasonic meters to mis-measure the flowrate. Figure 39 shows an example of an ultrasonic meter diagnostic system output caused by disturbed flow. While Venturi meters are rather resistant to disturbed flow, they are not immune, and significant disturbance causes the Venturi meter to also mis-measure the flowrate.

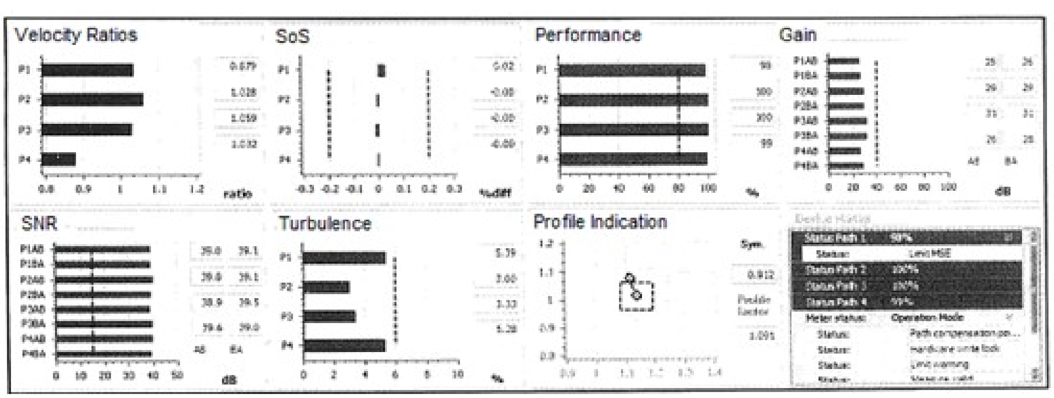

Figure 39. Ultrasonic Meter Disturbed Flow Diagnostic Result.

Figure 40 shows the Venturi meter Prognosis output caused by disturbed flow and the ultrasonic meter diagnostic output of Figure 39 converted to the simple form shown in Figure 38. The respective flow meter diagnostic pattern recognition techniques produce respective short lists. Individually neither meter's diagnostic system can isolate the problem. But by cross-referencing the two meter diagnostic outputs the specific problem becomes clear.

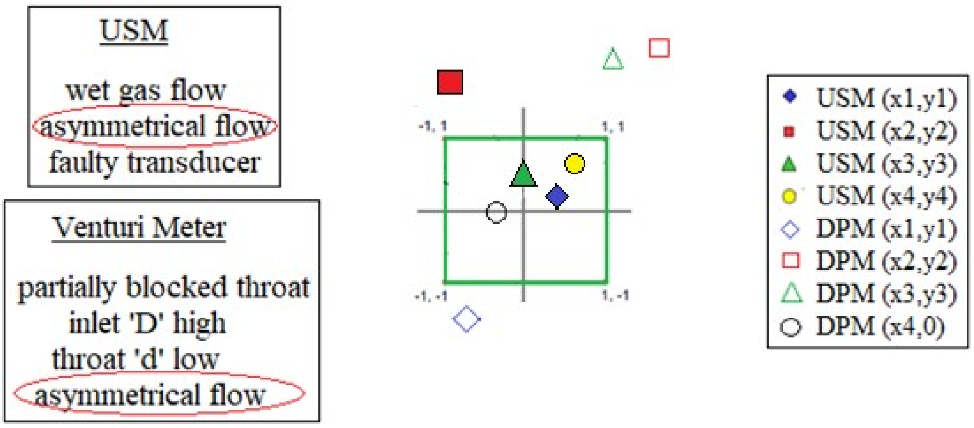

Figure 40. Ultrasonic and Venturi Meter Diagnostic Reaction to Disturbed Flow.

8.2 Example 2: PVT / Equation of State Problem

Both the ultrasonic and Venturi gas flow meters are dependent on the external input of the fluid properties, specifically the gas density, to predict the mass flowrate, or standard volume flowrate. Any bias in this density input will skew both meters mass flowrate output. Figure 41 shows an example if the external gas density input has a bias.

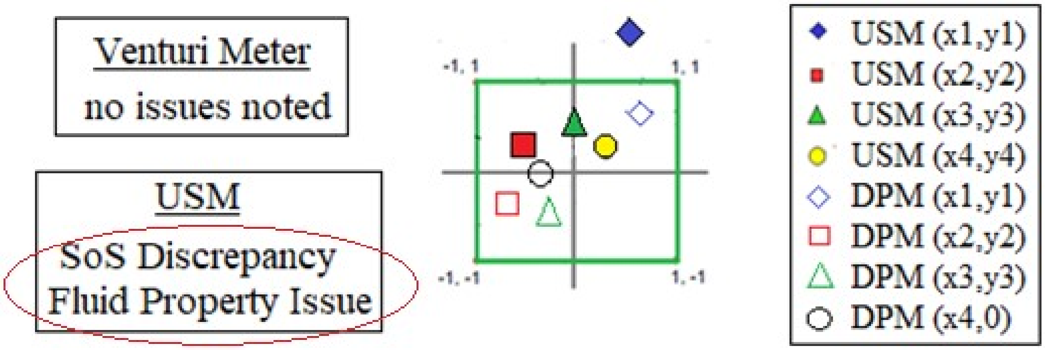

Figure 41. Ultrasonic and Venturi Meter Diagnostic Reaction to Biased Gas Property Prediction

The gas properties supplied include the density and the SoS. The Venturi meter Prognosis system is insensitive to these fluid properties and does not indicate any problem. However, the ultrasonic meter diagnostic system is sensitive to SoS. Figure 41 shows the ultrasonic meter y1 diagnostic check (i.e. the internal to external SoS comparison) showing a problem. This SoS alarm alerts the user to the fact that the fluid properties in general, inclusive of the gas density are questionable, and therefore so are both these meters mass flowrate predictions. This example shows that in some cases cross referencing different meter diagnostics can lead to one metering systems diagnostic seeing an issue the other cannot, thus helping both meters, or a hybrid meter.

The other density input check is to take the ultrasonic meter as a density insensitive volume meter, and the Venturi meter as a density sensitive volume meter, and predict density via Boden's method, to comapre with the external density input. The ultrasonic meter's SOS check is generally able to see smaller density issues that the Boden method.

Example 3: Wet Gas Flow

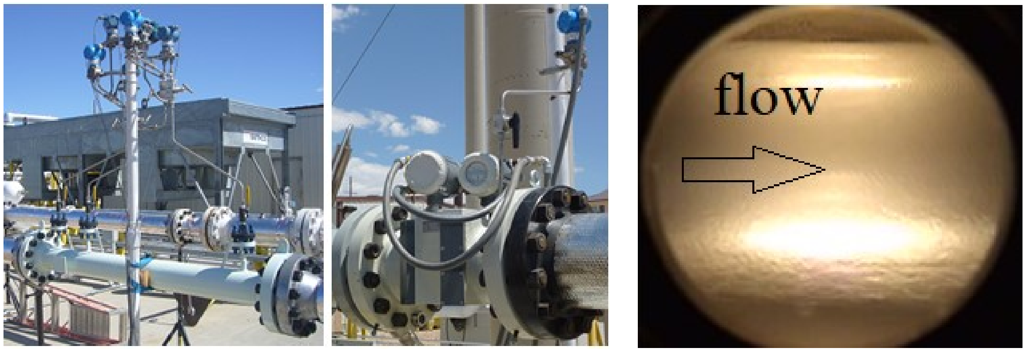

Figure 42. Venturi and Ultrasonic Meters Under Wet Gas Flow Testing.

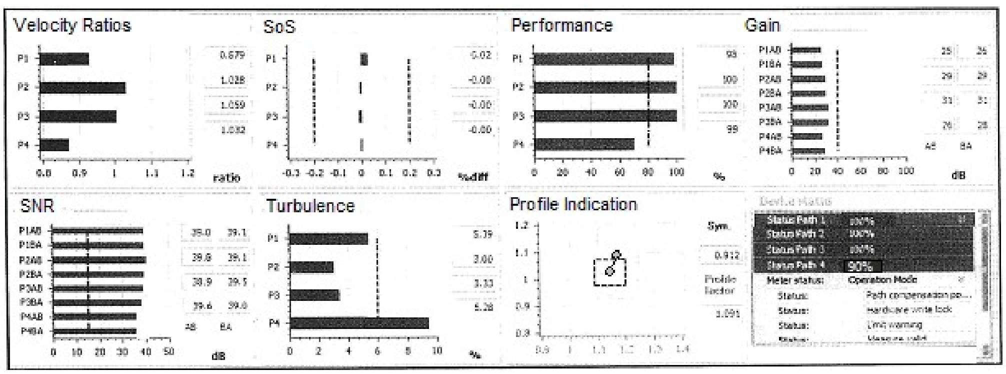

Figure 43. Ultrasonic Meter High Liquid Loading Wet Gas Diagnostic Result.

Wet gas flow is an adverse flow condition to all flow meter designs. Figure 42 shows a Venturi meter (with Prognosis) and an ultrasonic meter during wet gas flow testing. It takes a moderate liquid loading (typically LVF>1%) and a corresponding moderate flow prediction bias (>3%) before an ultrasonic meter diagnostic system identifies a problem. Venturi meter Prognosis is more sensitive to wet gas flow than ultrasonic meter diagnosticss. Figure 44 shows the comparitive diagnostic results at a LVF of 0.05% The Venturi meter Prognosis shows there is a problem at this low liquid loading. The ultrasonic meter diagnostic is not sensitive enough to see this amount of liquid and indicates all is okay. Both meters have an approximate +3% gas flow prediction over-reading. As the ultrasonic meter diagnostic suite covers for the Venturi meter Prognosis system when there is a fluid property problem, the Venturi meter Prognosis covers for the ultrasonic meter when there is low liquid loading wet gas flow.

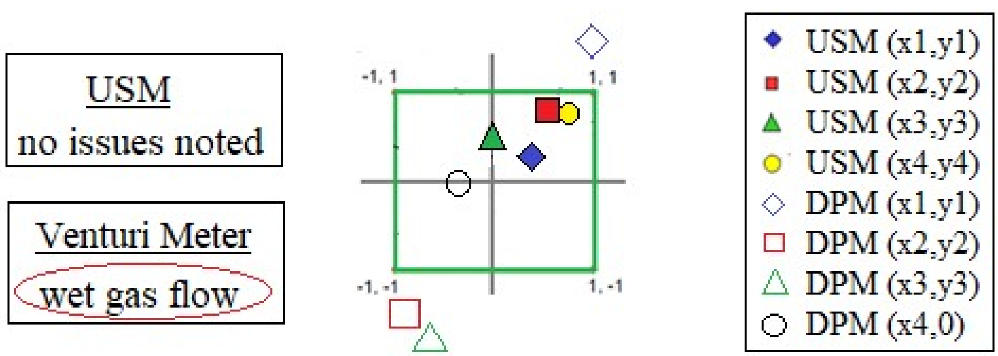

Figure 44. Ultrasonic and Venturi Meter Diagnostic Reaction to Wet Gas Flow.

9. CONCLUSIONS

Flow metering technology has never been so sophisticated, diverse and capable. These diverse individual meter designs based on single physical principles have each got their pros and cons, and together offer the user a great variety of choice. However, these common mainstream individual flow metering technologies are now well developed, and further developments tend to produce only incremental improvements. And yet, industry has various challanging flow metering applications with as yet no satisfactory solution is readily available.

The flow metering community tends to be balkanized into sub-communities that prefer one of these meter types over the others. Although, proponents of one meter type do not tend to see the world in this way, in reality choice of any one flow meter type over the other options inherently includes a compromise, i.e. the rejection of one set of pros and cons for another.

With modern electromechanical manufacturing and computing capabilities there is today the option to start combining different flow meter technologies into single hybrid meter bodies. This offers the ability to combine different flow metering principles pros, while covering for some individual meter type cons, thus making the resulting flow metering system altogether more capable than any standalone single physical principle flow meter. With modern manufacturing and computing capabilities this is in various cases both economically and technically achievable.

Different flow meter types, i.e. different flow metering principles, in a single hybrid flow meters can have a symbiotic relationship. There are the advantages of system redundancy, a greater variety of diagnostic checks, and extra measureable parameters making it possible to more easily meter some flows that were previously problematic. Hybrid flow meter design represents an understanding that different flow metering physical principles are not necessarily superior or inferior to each other, but simply represent different pros and cons. And when different flow metering principles are combined more often than not the whole is greater than the sum of it's parts. As is often the case, two are better than one, together they can work more effeciently than indiviual meter types alone.

Whereas many standard common place flow metering applications may not require such extra complexity and sophistication, various problematic flow conditions throughout industry would certainly benefit from such an approach. This is a flow metering option that should be considered for specific applications more often than it is.

Use of hybrid flow meter designs, i.e. the use of multiple flow metering principles together, shows a preference (figuratively speaking) for a polylithic approach to flow meter design over the traditional monolithic approach. A polylithic design approach encourages individual sub-systems that can individually operate well, but can do much more when combined in various ways.

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