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A Hybrid Wet Gas Meter Design for Marginal Fields

E Sanford[1], K Igarashi[2], R Steven[3]

[1]Vortek Instruments, Fredrick, Colorado, USA
[2]AZBIL, Fredrick, Colorado, USA
[3]DP Diagnostics, Windsor, Colorado, USA
esanford@vortekinst.com

Abstract

Combining different metering physical principles into one metering system offers various advantages. In this paper the advantages of producing a hybrid vortex and cone DP meter system is discussed. In single phase flow applications this hybrid meter produces a mass flow, volume flow, and fluid density predictions. In saturated steam and wet natural gas flow applications this hybrid meter can predict the two-phase flow quality, and total mass flow rate. The cone meter sub-system can also run the generic DP meter pressure field analysis diagnostic system 'Prognosis'.

1. Introduction

Natural gas onshore production is often from marginal wells. Such wells, or groups of wells, often produce wet natural gas through small pipes and therefore wet gas meters are desirable. However, most wet gas meter products are sophisticated, complex, and expensive systems largely aimed at offshore high productivity flows. They tend to be cost prohibitive for marginal well small pipe wet gas flows. Marginal field operation requires simpler, more cost effective, wet gas meter designs.

One simple wet gas meter design concept is use of two dissimilar gas meters in series. The two meter's different responses to wet gas flow are cross-referenced to produce a gas flow rate and liquid loading prediction. Such designs exist on the market, but they tend to use at least one specially designed meter and be expensive. This paper discusses a simple low cost two meters in series wet gas meter design. It pairs a vortex meter and a cone DP meter. It is developed from a single phase mass meter design.

2. <u>A Single Phase Flow Mass Meter – A Hybrid Vortex and Cone DP Meter System</u>

Direct mass flow metering means the metering of mass flow without the fluid density value being required from a source external to the meter. There are various ways of doing this, e.g. critical nozzle, Coriolis, and 'Boden' mass meter designs. Naturally, each of these physical principles have pros and cons. For example, critical nozzles operate with very clean gas flows only, and have relatively high pressure loss. Coriolis meters have a large footprint and are relatively expensive.

The Boden mass flow meter design principle is simple, has a long history, is publicly available technology, but is not widely known. In 1956 Boden, an engineer in the aerospace industry, proposed pairing a density insensitive volume meter (e.g. a turbine meter) in series with a density sensitive volume meter (e.g. a Differential Pressure meter). The density insensitive meter predicts the fluid volume flow rate without knowledge of the fluid density being required. The volume flow through the adjacent density sensitive meter is therefore now known. A stand-alone DP meter requires the fluid density be supplied in order to predict the volume flow. However, the calculation can be reversed. With a known volume flow rate the DP meter equation predicts the fluid density. The mass flow prediction is simply the product of the predicted volume flow and density. This is the simplicity of the Boden principle.

However, with this Boden principle, the devil is in the detail. The idea more than half a century old, but only with the advent of modern computers is such a system industrially practical. But even then, few end users want two separate meters in series. That is potentially expensive, has a large footprint, and brings images of a contraption. A practical Boden mass meter design must be compact, effectively operate as a single entity, a simple hybrid design blending the two separate meter principles together. However, that's easier said than done. There are two significant problems for the designer:

a) A common limitation of different flow meter designs is that their performance is adversely affected by disturbed flow. It is therefore a challenge to find a combination of meters that can operate in close proximity to each other and not be adversely affected by each other's presence.

b) When two different metering principles are blended into one design, i.e. are placed together, it can become challenging to independently design the two sub-systems such that they operate across the same flow range. It is a requirement that the density sensitive and density insensitive meters have the same flow range if they are to be successfully paired.

Most early Boden mass meter designs failed to pass the development stage and make it to market as the designers either failed to recognize the importance of, or simply failed to accomplish, these two essential requirements. The VorCone™ meter is a Boden design hybrid vortex meter and cone DP meter that meets these two requirements. Figure 1 shows a sketch of the system. The vortex meter is a density insensitive volume meter. The cone DP meter is a density sensitive volume meter. Sanford et al [1] discusses the development in detail.

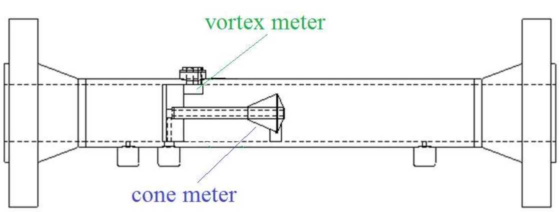

Fig 1. VorCone Meter Schematic

The vortex meter is upstream of the cone meter and receives the undisturbed inlet flow. The vortex meter performance is unaffected by the cone meter downstream. The cone meter assembly uses the vortex shedding bar as the cone meter support. The gusseted cone is set back such that the apex of the cone is downstream of the vortex shedding sensor. The cone element is positioned in the vortex meter's wake. However, the generic cone DP meter is renowned for its resistance to disturbed flows (e.g. see ISO 5167-5 [2]). Multiple prototypes tested over several years of development have honed the VorCone meter design such that the cone meter is also now shown to be unaffected by the close upstream proximity of the vortex meter.

$$Q_v = f/K \quad (1)$$

$$Q_v = \frac{A\beta^2}{\sqrt{1-\beta^4}} Y C_d \sqrt{\frac{2\Delta P}{\rho}} \quad (2)$$

$$\rho = 2\Delta P \left\{ \frac{K Y C_d}{f} \frac{A\beta^2}{1-\beta^4} \right\}^2 \quad (3)$$

$$Q_m = \rho Q_v \quad (4)$$

The vortex meter predicts the volume flow rate (Q_v) via equation 1, where '*f*' is the vortex shedding frequency, and '*K*' is the vortex meter factor. Equation 2 represents the cone DP meter volume flow rate equation. Note, *A* is the inlet area, β is the beta (i.e. cone size parameter), *Y* is expansibility (i.e. the correction for any density fluctuation through the meter), C_d is the cone 'discharge coefficient' meter factor, ΔP is the differential pressure, and ρ is the fluid density. Substituting the volume flow prediction of equation 1 into equation 2 gives a density prediction (see equation 3). Mass flow is found from the volume flow rate and density prediction (see equation 4).

2.1 3" VorCone Meter Gas Flow Laboratory Test

Figure 2 shows a photograph looking downstream into a 3" gas VorCone meter. Figure 3 shows this meter under test in a CEESI gas calibration facility. Figures 4 & 5 show the cone and vortex meter sub-system independent calibration results. Figure 6 shows the gas mass, volume, and density predictions compared to the CEESI test facility references. The meter was tested with air flow at 810, 400, & 150 psia across a 10:1 flow range. The volume flow is predicted to 0.5%, the mass flow to 1%, and the density to 1.5% all at 95% confidence level.


Fig 2. 3" VorCone Meter.

Fig 3. 3” VorCone Meter Gas Tested at CEESI.

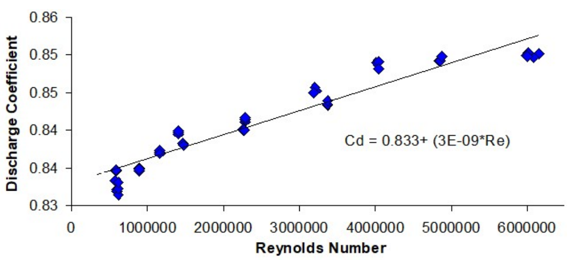

Fig 4. Cone Meter Sub-System Calibration of 3” VorCone Meter.

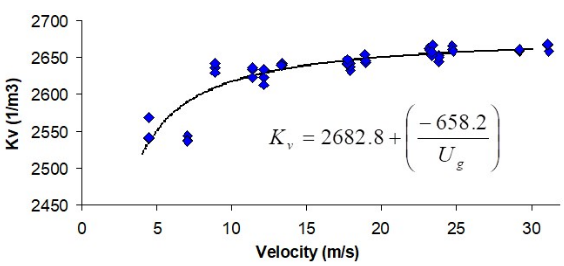

Fig 5. Vortex Meter Sub-System Calibration of 3” VorCone Meter.

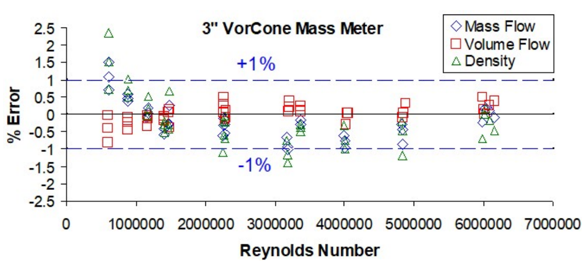

Fig 6. 3” VorCone Meter Gas Mass, Volume, and Density Prediction Results

2.2 4” Meter Liquid Laboratory & Field Tests

Oil is transported from some local well storage facilities by truck (e.g. Figure 10). The storage facility measures the oil quantity being loaded via volume change in the storage tank. The truck has an independent check meter. The loading and unloading oil quantity must match between the truck flow meter and storage facility measurements. However, the oil density can change between batches. Hence, a mass meter is preferred on the truck. Sometimes Coriolis meters are used. However, with excessive vibration whilst the truck is in motion on unpaved surfaces, fluctuating flow rates while in operation, start / stop induced errors etc., the application is challenging for all meters designs. Under such adverse flow conditions the operator reported a typical mass flow uncertainty of approximately 1% from the Coriolis meters. Two 4” VorCone meters were tested.

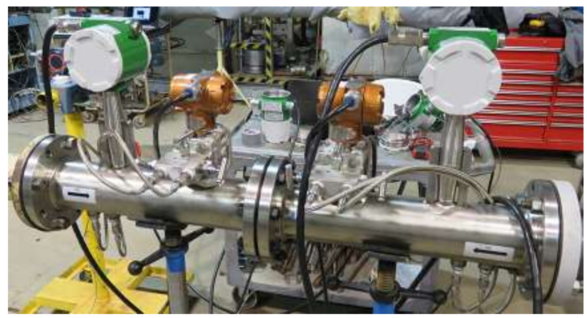

Fig 7. Two 4” VorCone Meters Close Coupled For Bi-Directional Application Under Calibration at the CEESI Water Facility.

As the VorCone meter is unidirectional and the truck loads and unloads through a single pipeline two close coupled meters were installed, one for each direction. Figure 7 shows these meters during calibration in this configuration at the CEESI water flow facility. Figures 8 & 9 show the calibrations results. Both meters predicted the volume and mass flow rates to < 1% uncertainty and the density to < 1.5% uncertainty (at 95% confidence).

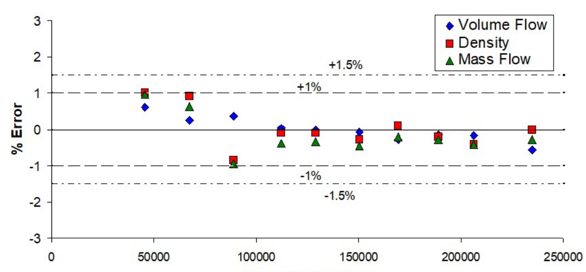

Fig 8. CEESI Water Flow Calibration Results From First 4” VorCone Meter.

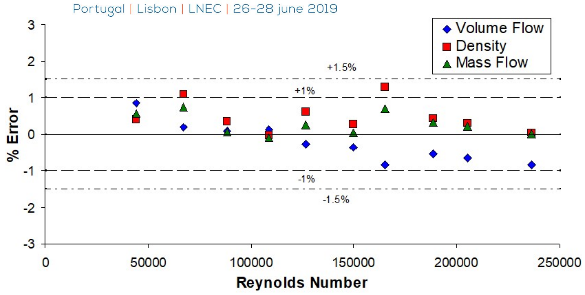

Fig 9. CEESI Water Flow Calibration Results From Second 4" VorCone Meter.

Fig 10. Truck with 4" VorCone Meters Installed.

Figures 10 and 11 show the truck and the installed meters respectively. These meters were used in multiple oil transfers. The data was recorded in batches (i.e. the run counter) that sum to the total batch quantity. As reported for the Coriolis meters there was a reasonable amount of scatter between run counts. Figure 12 shows the results with the authors estimated facility storage tank reference uncertainty of 0.5% error bars included. Both VorCone meters predicted the flow to 1% uncertainty. However, as with the Coriolis meter, the totalized oil quantity values for loading and unloading

Fig 11. Oil Truck Mounted 4" VorCone Meters

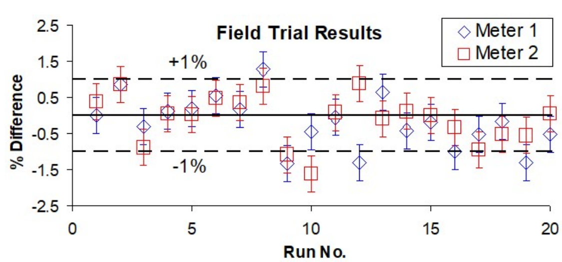

Fig 12. Truck 4" VorCone Meter Performances Compared to Facility Reference.

over the 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. No zeroing / re-calibration was required in the field.

	Reference 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.

3. Saturated Steam Flow

In 2015 an oil company investigated if the VorCone meter could be used in a 'heavy oil' field saturated steam injection application. The VorCone meter was used to predict the saturated steam quality (x) and monitor for quality changes. Steam quality, sometimes called 'dryness fraction', is defined by equation 5, where m_g and m_l denote the mass flow of steam (i.e. steam vapor / gas) and liquid (i.e. water).

Saturated steam is the carrier mechanism to inject heat into the well to reduce the oil viscosity and make it easier to extract. Saturated steam is an expensive commodity,

$$x = \frac{m_g}{m_g + m_l} \quad (5)$$

$$Q_{v,Total} = f/K$$

(1a)

$$\rho_{\text{hom}} = 2\Delta P_{tp}\left\{\frac{KYC_d}{f}\frac{A\beta^2}{1-\beta^4}\right\}^2 \quad (3a)$$

$$x = \frac{\rho_g\left(\rho_l - \rho_{\text{hom}}\right)}{\rho_{\text{hom}}\left(\rho_l - \rho_g\right)} \quad (6)$$

requiring 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 pipe line. 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.

Industries research into wet gas flow metering has found that the liquid dispersion in the gas phase strongly dictates the flow meter's reaction to its presence. (For example, see ASME MFC 19G [3]). For a given pressure and gas velocity a major factor dictating the liquid dispersion is known to be the liquid's surface tension. For horizontal flow, the higher the surface tension the more tendency for the liquid to flow as a separated phase at the base of the pipe. The lower the surface tension the more the tendency for the liquid to flow as droplets suspended in the gas flow, i.e. a mist flow. Mist flow approximates to a pseudo-single phase homogenous mixture.

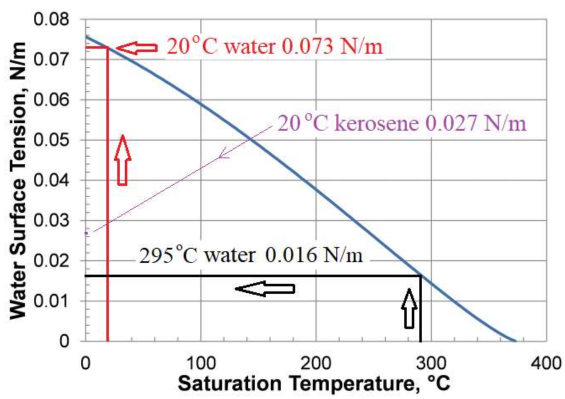

Fig 13. Fluid Surface Tensions

Saturated steam has $x \leq 100\%$, i.e. there is a mixture of steam / water (i.e. gas / liquid). Compared to wet natural gas at ambient temperatures saturated steam has a liquid phase (i.e. *very* hot water) with a very low surface tension. Figure 13 shows the approximate surface tension values for water and a light oil at 20°C, i.e. a typical wet natural gas production flow temperature. The water value is 0.073 N/m, the kerosene value is 0.027 N/m. Figure 13 also shows the surface tension of water at elevated temperatures. A saturated steam flow at 80 Bar / 295°C has a water surface tension of approximately 0.016 N/m, i.e. approximately five times less than the value at 20°C.

This facilitates the liquid being well dispersed in the steam vapor even at moderate gas velocities. Hence, if the local steam velocity is high the water and steam will be well mixed, and could be reasonably modelled as a homogenous mix. The meter itself further helps the mixing.

Hence, the vortex meter subsystem's volume flow prediction could be approximated to be the homogenous mix total volume ($Q_{v,Total}$). The cone meter's DP produced by the two-phase flow mixture (ΔP_{tp}) could be approximated to be the DP produced by a homogenous 'pseudo-single phase' mixture. Hence, Equation 1a produces a total volume flow prediction, and Equation 3a then produces a homogenous density prediction. With measured pressure and temperature the 'steam tables' supply the steam (ρ_g) and water (ρ_l) densities. Therefore, Equation 6 predicts the steam quality.

Fig 14. 3" VorCone Meter Saturated Steam Field Installation.

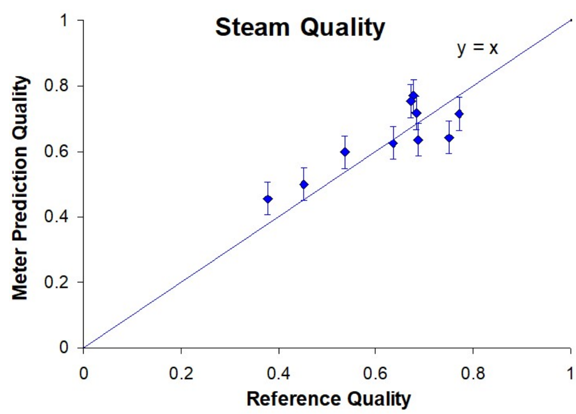

Fig 15. 3" VorCone Meter Saturated Steam Flow Quality Prediction Results.

Figure 14 shows a 2" VorCone meter during a heavy oil field saturated steam injection test. The saturated steam flow reference data was obtained from a downstream cyclone separator with single phase gas and liquid Coriolis meters at the outlets. Due to their nature field references are never as precise as laboratory references. It is estimated that due to the possibilities of imperfect separation and phase change after separation the field quality reference uncertainty was 5%. Figure 15 shows the resulting VorCone meter's quality prediction vs. the field reference values (with associated reference uncertainty bars). Whereas the direct measurement of saturated steam quality is notoriously difficult the fully theoretical steam quality prediction agrees with the reference data (with 5% uncertainty) to less than 10% uncertainty (i.e. x% ± 10%). Furthermore, changes in steam quality is clearly correctly tracked.

The hydrocarbon production industry tends to describe liquid loading not by quality (*x*), but by the 'Lockhart Martinelli' parameter (X_{LM}), see equation 7. Therefore, for a predicted quality, and known gas and liquid density values, the Lockhart-Martinelli parameter is also predicted. The steam vapor / gas flow through the VorCone meter can now be predicted using a correction factor. ISO TR 12748 [4] offers a cone meter wet gas correlation shown here as Equation set 8 thru 11. Note, $m_{g,App}$ is the 'apparent' gas mass flow predicted by the uncorrected meter, '*C*' is the Chisholm coefficient, '*n*' is the Chisholm exponent, '*g*' is the gravitational constant, '*D*' is the meter inlet diameter, and 'Fr_g' is the Froude number. The Froude number is a non-dimensional expression of the gas mass flow rate through the meter at set fluid densities. This equation set traditionally requires the liquid loading to be known from an external source, which the VorCone meter supplies. That is, for a predicted quality, i.e. predicted Lockhart Martinelli parameter, gas mass flow is solved by iteration of this equation set.

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

$$m_g = \frac{m_{g,App}}{\sqrt{1 + CX_{LM} + X_{LM}^2}} \qquad (8)$$

$$C = \left(\frac{\rho_g}{\rho_l}\right)^n + \left(\frac{\rho_l}{\rho_g}\right)^n \qquad (9)$$

$$Fr_g = \frac{m_g}{\sqrt{gD}}\sqrt{\frac{1}{\rho_g\left(\rho_l - \rho_g\right)}}$$
(10)

$$n = \frac{1}{2}\left\{1 - \left(\frac{0.83}{1.14\exp\left(0.31Fr_g\right)}\right)\right\} \qquad (11)$$

The percentage 'over-reading' (*OR*) is the steam / gas flow prediction positive percentage bias induced by the presence of the water / liquid. Figure 16 shows the uncorrected cone meter steam percentage over-reading (*OR*) when using the steam vapour density (from the pressure and temperature readings and the steam tables). Figure 16 also shows the effect of applying the wet gas correction methods, i.e. the results of using the VorCone meter's predicted quality (i.e. Lockhart-Martinelli parameter) with the ISO cone meter correction factor. Without correction the wetness of the steam can cause the steam vapor mass flow prediction to have > 30% over-reading. With the correction the steam vapour mass flow rate matches the reference data to < 5% uncertainty. As this is field data with relatively high reference uncertainties, it is very probable that laboratory data would show a significantly smaller steam vapor mass flow prediction uncertainty.

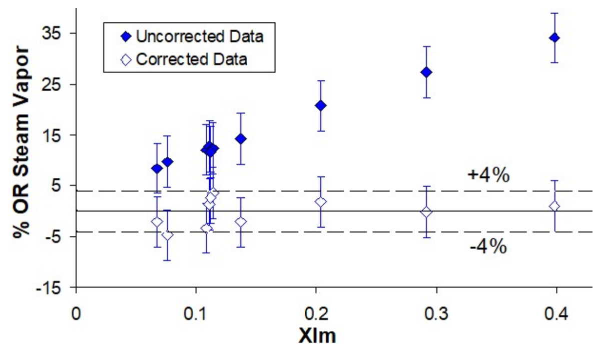

Fig 16. 2" VorCone Meter Saturated Steam Uncorrected and Corrected Steam Vapor Mass Flow Predictions.

Two 4" VorCone meters were subsequently installed at the outlet of a new steam boiler. There was no independent quality reference but the boiler was set to produce 75% steam quality. The meter read 73% steam quality.

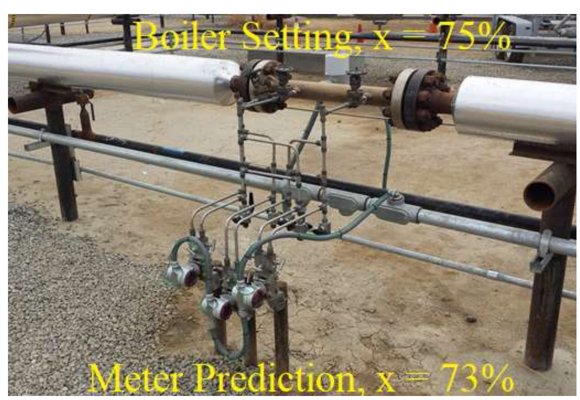

Fig 17. 4" VorCone Meter Installed at Outlet of Steam Boiler set to Produce 75% Quality Steam.

4. Wet Natural Gas Flow

A 4" to 3" reduced bore VorCone meter was tested at the CEESI wet natural gas flow facility (see Figure 18) with natural gas and kerosene flow at 35 Bar and ambient temperature. The kerosene at ambient temperature had a surface tension approximately 70% more than the field test's high temperature water (see Figure 13). It therefore takes more gas dynamic pressure to mix the kerosene than it does to mix hot water. That is, it takes a higher Froude number to produce a well-mixed gas / kerosene flow than a saturated steam flow. Therefore, this wet natural gas flow test is more challenging than the saturated steam flow test. A reduced bore design was used to increase the local gas velocity / Froude number at the meter.

Fig 18. 4" to 3" Reducer VorCone Meter at the CEESI Wet Gas Facility

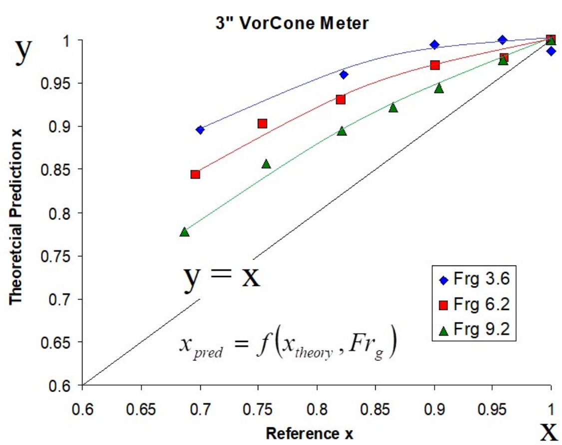

Fig 19. 3" VorCone Meter Theoretical Quality Prediction (No Fit) at the CEESI Wet Gas Facility.

Figure 19 shows the wet natural gas theoretical homogenous model quality prediction results for the quality range tested of > 65%. For all three flow rates the quality prediction clearly tracks the reference correctly. The higher the Froude number (i.e. the faster the gas flow) the better mixed the phases are and the better the corresponding theoretical homogenous model quality prediction. The data can be data fitted to give a more precise quality prediction. Figure 20 shows such fitted curves (Equation 12) on the data, where the quality prediction (x_{pred}) is related to the theoretical homogenous model steam prediction (x_{theory}) and the gas densiometric Froude number (see Equation 10).

$$x_{pred} = f\left(x_{theory}, Fr_g\right) \quad \text{--- (12)}$$

The quality prediction (x_{pred}) relationship with the gas densiometric Froude number (Fr_g) means that the quality and gas mass flow rate predictions are found by an iteration of Equation 12 and Equation set 7 thru 11.

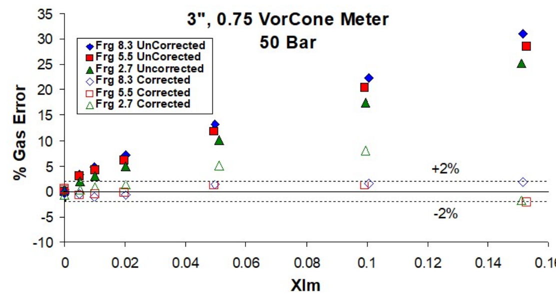

Fig 20. 4" to 3" Reducer VorCone Meter Uncorrected Cone Meter Over-Reading and with Correction Data Applied.

Figure 20 shows the VorCone meter's uncorrected gas flow rate prediction percentage error (or 'over-reading), and the gas flow rate percentage bias after the correction factor has been applied. Across the liquid loading range tested (i.e. $0 \le X_{LM} \le 0.15$ or 65% > x > 100%) for $Fr_g > 5$ the gas flow rate was predicted to 2% uncertainty at a 95% confidence level. For slower flow, i.e. $Fr_g < 5$, where there was less mixing, the bias was somewhat higher. However, it is important to note that for most applications the minimum local gas densiometric Froude number at the inlet to the meter is controllable via the common meter practice of matching the applications flow condition range to a reduced bore meter design. For example, a reduction from 3" to 2" schedule 80 increases the gas densiometric Froude number by 2.74 times. For most applications, proper reduced bore meter design can guarantee an appropriate local gas densiometric Froude number range and therefore successful wet gas operation.

The unofficial benchmark performance for the sophisticated and complex wet gas flow meter products tends to be metering the gas flow to 5% uncertainty. The unofficial benchmark performance for single phase gas meter designs with published correction factors is to have a gas flow prediction uncertainty (for *precisely* known liquid flow rates) of 2%. However, in the field the supplied liquid flowrate prediction has a significant uncertainty (typically up to 10%). Therefore, the reality of using a gas meter with a wet gas correction is that the real gas flow rate prediction uncertainty ends up being about 5%. Hence, a simple single phase meter design that can can predict the gas flow of a wet gas flow to <5% is a viable wet gas meter.

5. <u>An Additional VorCone Meter Liquid Loading Tracking Capability</u>

The cone meter sub-system of the VorCone meter operates as a standard cone DP meter. Therefore, the proprietary DP meter verification system 'Prognosis™' can be utilized. In wet gas / saturated steam flow applications Prognosis can give a second *independent* Lockhart Martinelli parameter / quality monitoring system, thereby giving liquid loading monitoring redundancy The following text gives an over-view of the Prognosis methodology.

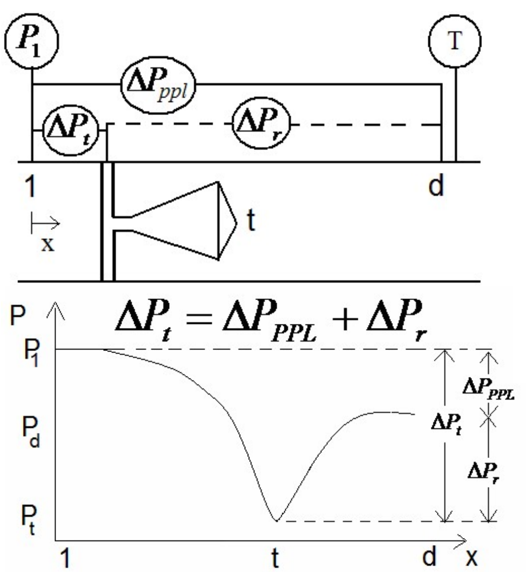

Figure 21. VorCone Meter with Instrumentation Sketch and Pressure Field Graph.

Figure 21 shows a sketch of a VorCone meter with a graph of the meter's pressure field. The meter has a third pressure tap downstream of the two traditional pressure ports. Note that the VorCone meter sketch of Figure 1 shows such a downstream pressure tapping, as do the photographs of VorCone meters shown in Figures 3, 14, & 17. The downstream tap allows three DPs to be read, i.e. the traditional (ΔP_t), recovered (ΔP_r) and permanent pressure loss (ΔP_{PPL}) DPs. These DPs are related by Equation 13. This relationship is a consequence of physical law and is therefore an objective diagnostic check on the health of the DPs read. The difference between the read ΔP_t and the sum of the read ΔP_r and ΔP_{PPL} cannot exceed the combined DP reading uncertainties.

DP Summation: $\Delta P_t = \Delta P_r + \Delta P_{PPL}$,
Uncertainty ± θ % (13)

Traditional flow calculation:

$$m = \frac{A\beta^2}{\sqrt{1-\beta^4}} Y C_d \sqrt{2\rho_g \Delta P_t} \text{ ,uncert } \pm x\% \quad (14)$$

Expansion flow calculation:

$$m = \frac{A\beta^2}{\sqrt{1-\beta^4}} K_r \sqrt{2\rho \Delta P_r} \text{ , uncert } \pm y\% \quad (15)$$

PPL flow calculation:

$$m = A K_{PPL} \sqrt{2\rho_g \Delta P_{PPL}} \text{ , uncert } \pm z\% \quad (16)$$

Each of the three DPs can be independently used to meter a single phase flow rate, as shown in Equations 14, 15 & 16. Note K_r and K_{PPL} denote the 'expansion' coefficient and 'PPL' coefficient of the expansion and PPL flow rate prediction methods. The three DPs turn the VorCone meter from one stand-alone meter to effectively a primary DP meter with two check DP meters. The three flow rate predictions give three pairs of flow rate predictions for comparison. The difference between any two flow rate predictions cannot exceed the combined flow rate prediction uncertainties.

The three read DPs produce three pairs of DPs, i.e. three DP ratios. Such DP ratios of any generic DP meter are known to be characteristics of a DP meter. They do not change with changes in single phase flow conditions. The three DP ratio baselines are set during the VorCone meters calibration. Comparison of each found to expected (baseline) DP ratio produces three diagnostic checks. For each of the three DP ratios the difference between the found to expected (baseline) DP ratio cannot exceed the calibration baseline values uncertainties.

The three flow meter coefficients C_d, K_r, & K_{PPL} and the three DP ratios are found during the standard calibration of the flow meter.

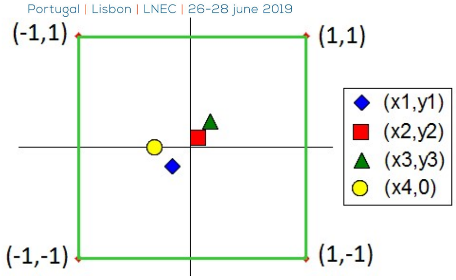

Fig 22. Diagnostic results

The seven diagnostic results are shown on a graph (Figure 22) as four co-ordinates (x_1,y_1), (x_2,y_2), (x_3,y_3) & (x_4,0). Note, x_4 represents the DP reading integrity check. The three other 'x' values represent the three flow rate prediction comparisons. The three 'y' values represent the three DP ratio found to expected comparisons.

All points inside the box indicate a serviceable cone meter. One or more point/s outside the box represent/s a potential problem. The pattern of point distribution gives indications of possible problems. Two-phase flow, i.e. saturated steam (x < 100%) or wet natural gas (X_{LM} > 0) produces a specific Prognosis pattern.

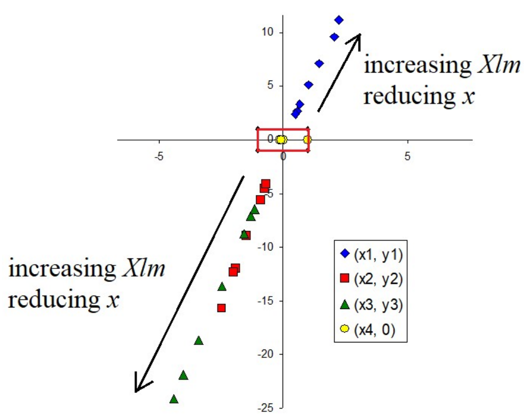

Fig 23. 3" VorCone Meter Prognosis Result at 35 Bar, 300 m^3/hr

Figure 22 shows a typical Prognosis verification system result for the 3" VorCone meter tested with single phase natural gas at CEESI (see Figure 18). As required all points are inside the box indicating a fully serviceable correctly operating cone meter.

Figure 23 shows the subsequent Prognosis results when the 3" VorCone meter installed in the CEESI wet gas facility was subjected to varying liquid loading wet gas flows at the 35 bar, and 400 m^3/hr. For display clarity, the abscissa (x) and ordinate (y) axes have been changed in scale relative to each other. Prognosis clearly indicates a problem, i.e. points are out the box. This is a typical Prognosis wet gas flow pattern. Coordinate (x_1, y_1) is in the first quadrant, while (x_2, y_2) and (x_3, y_4) are in the third quadrant. The DP reading check, i.e. (x_4, 0) is unaffected by the presence of wet gas flow. As the liquid loading increases (i.e. the quality reduces / the Lockhart Martinelli parameter increases) the points diverge from the origin and the box, and vice versa. This is a method of tracking liquid loading that is independent of the primary VorCone meter method described in Sections 3 and 4.

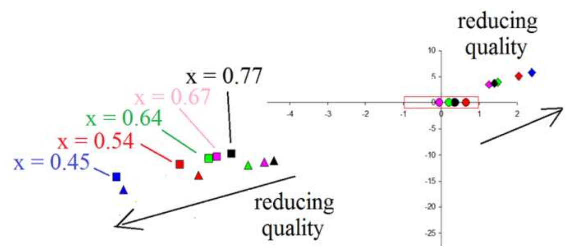

Figure 25. 2" VorCone Meter Prognosis Field Response to Changes in Saturated Steam Quality.

Figure 25 shows the 2" VorCone meter Prognosis response during the saturated steam injection oil field test (see Figure 14). During the test the quality was varied between 45% and 77%. Prognosis showed the flow was two-phase (x < 100%) and correctly tracked the changes in quality.

6. Conclusions

The VorCone meter is a hybrid vortex and cone DP meter. It is a Boden type single phase mass flow meter. The design has blended the two separate flow metering principles into one meter body such that the two meters do not have adverse effects on each other's performance. The VorCone meter has been shown with laboratory and field trials to be a capable single phase gas or liquid mass flow meter and densitometer. The VorCone meter can operate with the DP meter verification system Prognosis.

The VorCone meter can be used in the adverse flow conditions of saturated steam or wet natural gas flow. Moderate to high local gas velocities, that if necessary can be assured by an appropriate reduced bore meter design, allow the meter to track liquid loading using only theoretical principles. Reduced bore designs are common across many meter designs. Furthermore, a flow quality / liquid loading data fit allows the VorCone meter to predict the gas flow rate of a wet gas flow. The 3" VorCone meter tested at the CEESI wet gas facility predicted the gas flow to 2% uncertainty for a quality range of x > 65%. This is industrially useful, as many steam quality meters / monitor designs only operate at x > 90%.

Finally, the cone meter verification system 'Prognosis' can monitor the health of the cone meter sub-system in single phase flow, and can track changes in wet gas flow liquid loading independently of the main metering system liquid loading prediction method. This means that the VorCone meter has the rare feature of redundancy in liquid loading tracking methods.

7. References

1. Sanford E. et al "Gas Mass Flow Metering – An Alternative Approach" North Sea Flow measurement Workshop, Tonsberg, Norway, 2015

2. ISO 5167-5:2016 "Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -- Part 5: Cone meters".

3. ASME MFC 2008 Report 19G "Wet Gas Metering".

4. ISO TR 12748 "Natural Gas –Wet Gas Flow Measurement in Operations".