A Mass Flow Meter Concept with Diagnostic Capabilities

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Abstract:
A simple, accurate, relatively compact and light gas mass flow meter has been developed with diagnostic capabilities. This fundamental mass flow meter concept revises a simple concept originally suggested four decades ago before the computer power existed to make a practical system. This paper revises the concept, discusses the development of a modern meter design and adds new diagnostic capabilities. The mass meters outputs are the volume flow rate, the fluid density and the mass flow rate. The system does not require the fluid density from an external source and can meter gas mass flows and measure gas density at low pressures. The system has significant qualitative diagnostics capable of signaling when the meter is malfunctioning. In cases where the fluid density is known from an external source some quantitative diagnostics are also available.

Keyword: mass meter, volume meter, densitometer, diagnostics.

1. Introduction

The direct metering of pipeline fluid mass flow rates is very desirable to industry. However, it has proven extremely difficult to meter an industrial pipelines flow directly by mass. Linear flow meter generic designs, i.e. flow meters where the sensor reading is linear to the average velocity of the flow, produce volume flow rate outputs only. To find the mass flow rate from linear flow meters the fluid density must be supplied from an external source. Linear flow meter designs include ultrasonic meters, turbine meters and vortex meters. Other flow meter generic designs, such as differential pressure (or "DP") meters, require the fluid density be supplied from an external source before either the volume or mass flow rate can be determined. There are very few direct mass flow rate meter generic designs. The dependency of most flow meters on externally supplied fluid density information both makes the independent measurement of density an expensive necessity and exposes the meter operator to metering errors through density prediction errors. Hence, often direct mass flow metering can be attractive. Furthermore, with most industries placing an increasing importance on both accurate and reliable flow metering, flow meter diagnostics are becoming more important. If there is a need for the flow meter to be purchased and installed then there is also a need to know you can trust the meters outputs when in service.

In this paper a little known, simple but effective, generic mass flow rate meter design first suggestion by Lisi [1] in 1974 is discussed. Lisi showed that a linear meter (in particular a vortex meter) and DP meter pair installed in series could be cross referenced to produce a metering system that gave the volume flow rate, mass flow rate and fluid density as outputs with no external fluid density prediction required. A modern meter design based on this generic concept is described and recent test data is shown. Furthermore, the original concept is developed further with the addition of new DP meter diagnostic concepts (as described by Steven [2]). Some diagnostic system worked examples are also given.

2. The Lisi Mass Flow Meter Concept

In 1974 Lisi [1], stated the benefits of placing vortex and orifice plate meters in series. He showed that this arrangement produced a combined volume and mass flow rate metering system and densitometer system. He also suggested that the vortex meter bluff body could be used as a DP meter primary element as well as a vortex shedding device hence alleviating the need for an independent DP meter system. That is, he had produced a hybrid vortex / DP meter where the whole was greater than the sum of its parts. In order to understand this mass flow meter concept and develop it let us first review the individual fundamental concepts of vortex shedding flow meters and DP flow meters.

2a) Vortex Shedding Flow Meter

Vortex meters expose a bluff body to the fluid stream. This causes the cyclic shedding of vortices from the bluff body (see Fig. 1). That is, a "von Karman vortex street" is created downstream of the bluff body. Experiments have shown that this vortex shedding frequency (f) is related in a linear fashion to the average free stream velocity. Therefore, reading the vortex shedding frequency allows the prediction of the average *velocity* of the fluid in the pipe. Knowing the flows average velocity and the internal pipe diameter allows the calculation of the *volume* flow rate. Vortex meters (and all linear meters) give the volume flow rate without requiring the fluid density as an input[1] but they require to be given the fluid density (from an external source) in order to predict the mass flow rate.

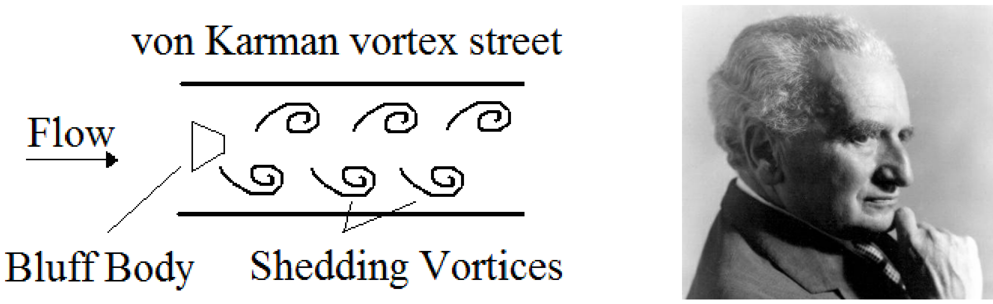

Fig. 1 Von Karman (right), and the principle of cyclic vortex shedding from a bluff body.

The volume and mass flow rates ($\dot{Q}$ & $\dot{m}$ respectively) are calculated by the vortex meter flow computer via equations 1 & 2 respectively. Note that " K_f " is the vortex meter "K-factor" which is usually found by calibration and ρ is the fluid density.

$$\dot{Q} = \frac{f}{K_f} \quad \text{--- (1)} \qquad\qquad \dot{m} = \rho\dot{Q} = \rho\frac{f}{K_f} \quad \text{--- (2)}$$

Experiments have shown that a constant K-factor (K_f) can usually be used over a moderate turn down. Hence, in this case the volume flow rate prediction is therefore independent of the fluid density. However, over a large turndown the K-factor *may be* found to be mildly sensitive to the Reynolds number (Re). In this case calibration allows a K-factor vs. Re fit (say function " g_1 " as shown in equation 3) i.e.:

[1] Some linear meters have meter factors mildly sensitive to the Reynolds number and therefore the fluid density. However, this is a second order effect and linear meters can typically predict the volume flow rate to relatively low uncertainty with a constant meter factor.

$$K_f = g_1(\text{Re}) \text{ -- (3)} \quad \text{where} \quad \text{Re} = \frac{4\dot{m}}{\pi\mu D} = \frac{4\rho\dot{Q}}{\pi\mu D} \text{ -- (4)}$$

Note μ is the fluid viscosity and D is the meters inlet diameter. Therefore:

$$\dot{Q} = \frac{f}{K_f} = \frac{f}{g_1(\text{Re})} = f \Big/ g_1\left(\frac{4\rho\dot{Q}}{\pi\mu D}\right) \text{ --- (5)}$$

If the effect of Reynolds number on the meter factor is large enough that equation 5 is required then the calculation of volume flow rate is dependent on density. In a typical application the operator will usually obtain the fluid density from an external source and therefore, the meters volume flow rate calculation uncertainty is related to the density uncertainty. Equation 5 is solved by iteration on the volume flow rate. For a more in-depth discussion on vortex shedding flow meter technologies see Storer [3].

2b) Differential Pressure (DP) Flow Meter Theory

Clemens Herschel developed the first DP meter in 1885. Herschel's "Venturi meter" was developed from the work of Giovanni Venturi which in turn developed work of Daniel Bernoulli (see Figure 2). Herschel reduced the cross sectional area of the flow by introducing a converging section that connects to a constant small area pipe (sometimes called the "throat") before returning the flow to the original pipe area by a diverging section (or "diffuser") as shown in Figure 3. The reduction in area increases the fluid velocity and reduces the local pressure in the flow. The difference in pressure between the inlet and throat is related to the flow rate.

Fig 2. Daniel Bernoulli (left), Giovanni Battista Venturi (middle), & Clemens Herschel (right).

Since Herschel's original Venturi meter design, different shapes of flow obstruction element (i.e. the "primary element") have been developed. However, they are all generic DP meters and they all operate according to the same physical principles. A generic DP meter creates a pressure field through the meter body that is dictated by the principle of conservation of mass and the first law of thermodynamics for an open system (i.e. the conservation of energy). A sketch of the pressure fluctuation through a Venturi meter is shown in Figure 3.

The principles of the conservation of mass and energy allows the flow rate to be calculated if the meter geometry is known, the fluid properties are known and a differential pressure between the meter inlet and minimum cross sectional area is measured. The same generic DP meter volume flow rate equation (i.e. equation) holds for different DP meter designs. The generic DP meter volume and mass flow rate equations are shown as equations 6 and 7.

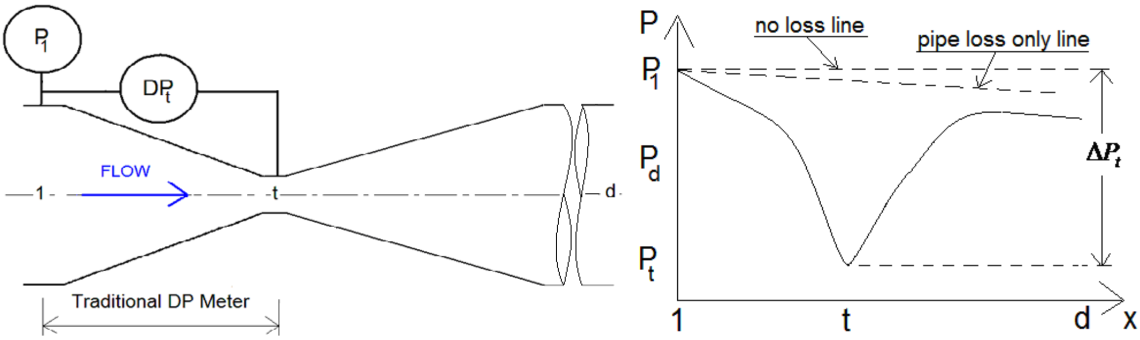

Fig 3. Venturi meter with instrumentation sketch and pressure fluctuation graph.

$$\dot{m} = EA_t YC_d \sqrt{2\rho\Delta P_t} \quad \text{-- (6)} \qquad \dot{Q} = EA_t YC_d \sqrt{\frac{2\Delta P_t}{\rho}} \quad \text{-- (7)}$$

Note that E and A_t are meter geometric constants (called the velocity of approach and the throat area respectively). These values are set by the DP meter geometry. For gas flow the change in area causes a change in the pressure and hence a change in gas density. An expansion factor (Y) corrects for this. The expansion factor shown as equation 8 is a function of the line pressure (P), the gases isentropic exponent (κ) the meters beta ratio (β) and the read differential pressure (ΔP_t). Different DP meter designs have different expansion factors. They are found by experiment for each meter design. Note the beta ratio (β) is defined as the square root of the minimum cross sectional area (or "throat") to the inlet area (A), as shown by equation 9.

$$Y = g_2(P, \Delta P_t, \kappa, \beta) \quad \text{-- (8)} \qquad \beta = \sqrt{A_t / A} \quad \text{-- (9)} \qquad C_d = g_3\left(4\rho\dot{Q} / \pi\mu D \right) \quad \text{-- (10)}$$

Finally, note that the term C_d in equations 6 & 7 is the discharge coefficient. This is a meter dependent term that accounts for the difference between theory and actual performance. This term is found from either standards documents for set geometry and flow rate ranges or found by meter calibration. A DP meters discharge coefficient can be constant over a Reynolds number range or fitted to the Reynolds number as shown in equation 10. If a DP meters discharge coefficient is found by experiment (i.e. the meter is calibrated), then that data fit is specific to that particular meter. If the discharge coefficient is fitted to the Reynolds number then Equation 11 is solved by iteration on the volume flow rate (for a known fluid density). For a more in-depth discussion on DP meter flow meter technologies see Steven [4]. The discharge coefficient for the DP meter is directly analogous with the vortex meters k-factor. Equations 6 to 11 hold not just for Herschel's Venturi meter but for all generic DP meters, i.e. orifice plate, nozzle cone meters etc.

$$\dot{Q} = EA_t Y \left\{ g_3\left(\frac{4\rho\dot{Q}}{\pi\mu D} \right) \right\} \sqrt{\frac{2\Delta P}{\rho}} \quad \text{-- (11)}$$

2c) <u>Lisi's Hybrid Vortex and Orifice Plate Mass, Volume and Density Metering System</u>

Lisi stated that a vortex meters volume flow rate prediction is ***insensitive*** to the fluid density (thereby inherently assuming a constant meter factor, i.e. a vortex meter K-factor insensitive to

Reynolds number.) He then pointed out that a DP meters volume flow rate prediction is ***sensitive*** to the fluid density. That is, the vortex meters volume flow rate prediction is obtained from equation 1 and a DP meters volume flow rate prediction is obtained from combining equations 7. Therefore, Lisi realized that if these two meters were installed in series, and therefore measuring the same volume flow rate (assuming negligible density change for the case of gas flow between the meter locations), the volume flow rate results must equate. That is equating equation 1 & 7 gives equation 12. Lisi rearranged equation 12 to get an expression for the density (equation 12a).

$$\dot{Q} = \frac{f}{K_f} = EA_t Y C_d \sqrt{\frac{2\Delta P}{\rho}} \quad \text{-- (12)} \qquad\qquad \rho = (2\Delta P)\left(\frac{K_f Y C_d E A_t}{f}\right)^2 \quad \text{-- (12a)}$$

For the case where the meter flow coefficients (K_v & C_d) are constants, all the information in the right side of equation 12a is known from meter geometries, instrument readings and calibration data. (This statement inherently makes the reasonable assumption that for gas flow the fluid isentropic exponent is known or can be approximated.) Therefore, the density can be directly calculated. Note, that if the flow coefficients have been fitted to the Reynolds number then they are not directly known. However, here, using equations 3, 4, 10 & 12a, the Reynolds number value can be iterated to converge on the density, mass flow rate and volume flow rate values. It should be noted that in this arrangement, with the meters being in close proximity to each other, the individual meter performances can be altered from the performance they would have had if they were stand alone meters. However, calibration of the two meters while in position together should remove this issue by altering the vortex k-factor and DP meter discharge coefficients accordingly.

The vortex and DP meter combination produces a densitometer and a volume and mass flow metering system. Independently neither meter can predict the density or the mass flow rate. The vortex meter will predict the volume flow rate but not the density or the mass flow rate. The DP meter can not predict the density, nor the mass and volume flow rates. It is wholly dependent on being given the density from an external source before it can predict either the mass and volume flow rates. Both meter types therefore individually traditionally have a mass flow rate uncertainty dependent on the externally found density uncertainty. This meter combination allows either the externally obtained density input to be checked by the meter system (i.e. a simple density diagnostic), or for applications where no density value is externally known, it allows density and mass flow rate readings. Therefore, the combination of vortex shedding and DP meters produced a system where the whole was greater than the sum of its parts.

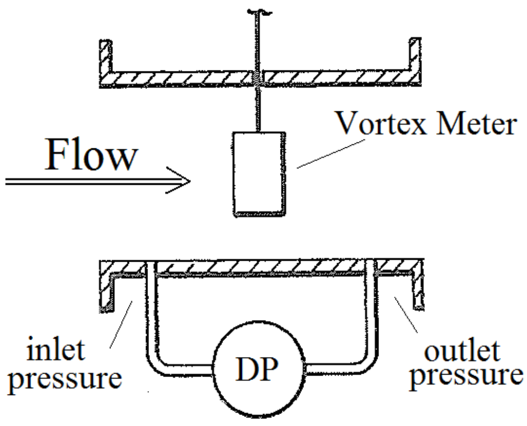

Fig 4. Lisi's Mass Meter Arrangement

Lisi went on to state that the DP meter could potentially be dispensed of altogether, as the vortex meters bluff body could be used as both the vortex producer and the DP meter primary element. That is, he suggested instead of having two independent meters in series, a more compact design would be to create a hybrid vortex / DP meter. Fig 4 shows a scan of Lisi's 1974 proposed set up (modified here for clarity). The vortex meter bluff body is being used as a DP meter. From this comment it can be inferred then that Lisi understood that the particular design of DP meter utilized was unimportant. Any DP meter can potentially be used. On this note it is also an obvious step to realize that *any* linear flow meter could work. That is, the idea is not limited to vortex meters, e.g. we could use ultrasonic or turbine meters.

3. Vortex and Cone Meters in Series - a Diagnostics Capable Mass Flow Meter System

DP Diagnostics and VorTek Instruments have together researched the Lisi concept with modern DP meter and Vortex meter designs. The vortex meter was chosen for the linear meter. Compared to ultrasonic and turbine meters it is relatively inexpensive, rugged, reliable and like the other linear meters it has a large turndown. DP Diagnostics produced a cone DP meter design for the DP meter to be used in conjunction with the VorTek Instruments vortex meter design. The cone meter was chosen as the preferred DP meter design as it is well known to be extremely resistant to upstream flow disturbances. All flow meters of all designs are adversely affected by flow disturbances upstream of their inlet. However, the cone meter has an extreme resistance to disturbed flow at the meter inlet. (See Hodges [5]). Hence, it was recognized that if the vortex meter was upstream of the cone meter it would not be significantly affected by the flow disturbance induced by the close presence of the vortex meter bluff body. On applying the cone meter it was recognized that modern DP meter diagnostics (as explained for cone meters in detail by Steven [6]) can be utilized while the meter is installed downstream of the vortex meter. Before discussing the complete mass flow meter system it is first necessary to discuss the cone DP meter and the associated DP meter diagnostics, as these will be combined with the traditional cone meter and vortex meter outputs to significantly increase the systems capabilities.

3a. Cone DP Meter Diagnostic Capabilities

A sketch of a cone meter (with a cut away view) is shown in Figure 5. Flow is from left to right. The upstream port is shown as the first coupling. The low pressure port is in the cones wake. The pressure is read through a hole running from the centre of the back face of the cone along the cone centre line to the cone support bar and then up through the support bar to the low pressure coupling. Notice that here we also have a downstream pressure tap to allow extra DP measurements. This is necessary to create the diagnostic capabilities of the DP meter.

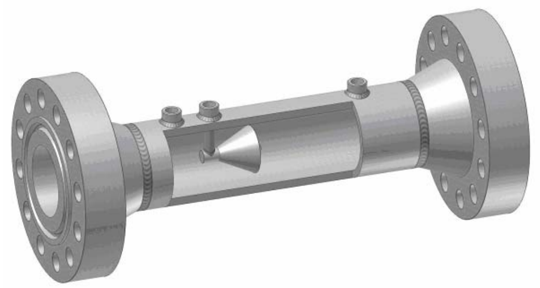

Fig 5. A Sketch of a DP Diagnostics ΔP Cone Meter

Figure 6 shows a sketch of the cone meter with a traditional set up of a pressure transmitter at the inlet and a DP transmitter between the inlet and the low pressure port (ΔP_t). However, a second

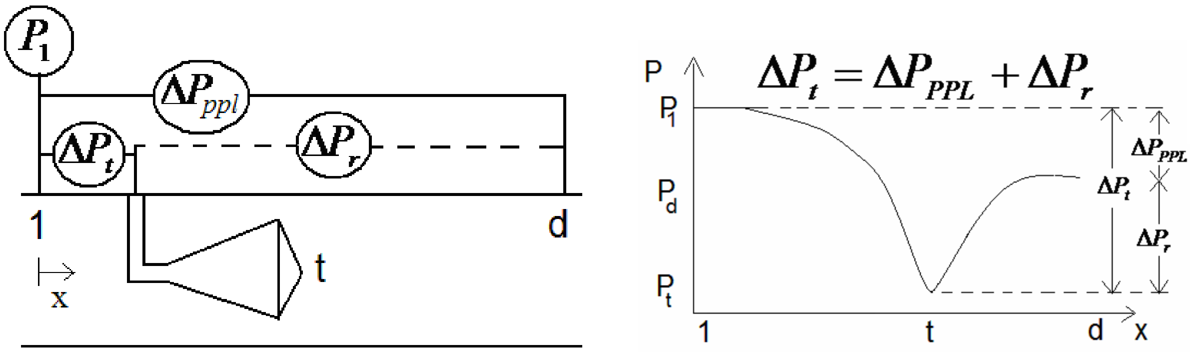

Fig 6. Cone DP meter with instrumentation sketch and pressure fluctuation graph.

DP transmitter is also attached to read the permanent pressure loss, or "head loss" (ΔP_{ppl}), across the cone meter. Figure 6 also shows the pressure fluctuations through the meter. Note that the difference between the traditional DP and the head loss is the recovered DP (ΔP_r) as shown by equation 13.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \text{-- (13)}$$

From Figure 6 and equation 13 it is clear that if a downstream pressure tap exists on a DP meter and a single extra DP transmitter is used, making a total of two DP transmitters, three DP's can be found. The same fundamental hydraulic theory that is used to derive the traditional generic DP meter flow rate equation for a converging section (i.e. equation 6) can also be applied to the recovered DP to derive a generic "expansion" DP meter flow rate equation for an expanding section (i.e. equation 14). Furthermore, hydraulic theory states that the head loss across a generic DP meter is directly related to the flow rate. This results in a permanent pressure loss, or "PPL" flow equation as shown as equation 15. Hence by adding a downstream pressure tap and one extra DP transmitter the generic DP meter now has three separate mass flow rate prediction methods.

Traditional Flow Equation: $\dot{m}_t = EA_tYC_d\sqrt{2\rho\Delta P_t}$, uncertainty ± x% --- (6)

Expansion Flow Equation: $\dot{m}_r = EA_tK_r\sqrt{2\rho\Delta P_r}$, uncertainty ± y% --- (14)

PPL Flow Equation: $\dot{m}_{PPL} = AK_{PPL}\sqrt{2\rho\Delta P_{PPL}}$, uncertainty ±z% --- (15)

In essence, by adding the downstream pressure tap and the extra DP transmitter the generic DP meter becomes three flow meters in one meter body. We now have three different methods of predicting the mass flow rate through the meter, the traditional prediction, $\dot{m}_t$, the expansion meter prediction $\dot{m}_r$ and the PPL meter prediction $\dot{m}_{PPL}$. It should be noted that in equation 14 the term K_r is the expansion coefficient and in equation 15 the term K_{PPL} is the expansion coefficient. These terms are directly analogous to the traditional meter discharge coefficient. They are found by calibration of the meter system. The discharge coefficient, expansion coefficient and the PPL coefficient can be fitted as a constant value or, for more accuracy, they can individually be fitted to the Reynolds number. A very detailed derivation of these three generic DP meter mass flow rate equations is given by Steven [2].

As the same mass flow flows through the same meter body all three of these DP meter mass flow rates should agree with each other (within their combined uncertainty limits). That is, for a correctly operating DP meter we can equate the three flow rate equations. This is the basis for DP meter diagnostics.

Finally, note that all generic DP meters share a common characteristic in that the ratio of the PPL (ΔP_{PPL}) to the traditional DP (ΔP_t), often called the pressure loss ratio (or the "PLR") is constant for a homogenous phase fluid flow through the meter regardless of whether the flow is a liquid or a gas, at high or low pressure, at high or low velocity etc.

3b. Combining the Vortex Meter with the Diagnostic Capable Cone DP Meter

If a vortex meter is installed in series with a diagnostic ready cone meter then there are four mass flow rate equations available, i.e. the vortex mass flow rate equation (equation 2) and the three DP meter flow rate equations (equations 6, 14 & 15). As all four mass flow rate equations are metering the same flow through the same meter system we can equate them, as done in equation set 16. That is we can compare the vortex meter flow rate equation to each of the three DP meter flow rate equations in turn. The equating of the vortex meter mass flow equation to any one of the DP meter mass flow rate equations produces an expression with one unknown, i.e. the fluid density, which can therefore be solved. That is, we have three separate ways of predicting the fluid density. If the system is operating correctly these three density predictions should agree within their associated uncertainties. Hence, we can equate the three fluid density predictions as a meter health check, as shown in equation set 16a.

$$\dot{m} = \rho \frac{f}{K_f} = EA_t Y C_d \sqrt{2\rho \Delta P_t} = EA_t K_r \sqrt{2\rho \Delta P_r} = AK_{PPL} \sqrt{2\rho \Delta P_{PPL}} \quad \text{-- (16)}$$

$$\rho = (2\Delta P)\left(\frac{K_f Y C_d E A_t}{f}\right)^2 = (2\Delta P)\left(\frac{K_f K_r E A_t}{f}\right)^2 = (2\Delta P)\left(\frac{K_f K_{PPL} A}{f}\right)^2 \quad \text{-- (16a)}$$

3c. The VorTek Instrument and DP Diagnostics Prototype Mass Flow Meter Design

The 4", schedule 80 prototype mass meter had the vortex bluff body placed upstream of the cone to avoid the possibility of the considerable wake of an upstream cone element adversely affecting a downstream vortex bluff bodies performance. The cone element was placed downstream of the bluff body because the bluff bodies flow disturbance was less than the wake of the cone element and the cone meter is known to be particularly resistant to upstream disturbances. The cone meter was the DP meter of choice as it is much more resistant to a vortex meters induced flow disturbance than any other DP meter on the market. The cone meters beta ratio was sized to give a similar flow range capability as the vortex meter. This was a beta ratio of 0.75.

For this initial investigation a spacing of 3D was given between the bluff body and the inlet pressure tap in front of the cone element. (It is suspected that the minimum practical distance is somewhat less than this.) Figure 7 shows photographs of the compact, sturdy, reliable and accurate volume and mass flow meter, come densitometer system. The flow computer casing is seen at the front of the system. It is connected above the vortex shedding bluff body. The vortex sensor instrumentation is also housed here. (The pressure tapping seen at 90 degrees to this location is for R&D work out with the scope of this technical paper.) Just upstream of the mid

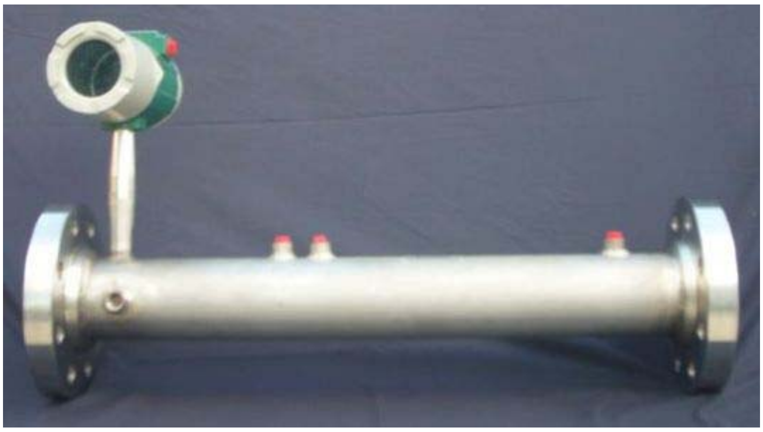 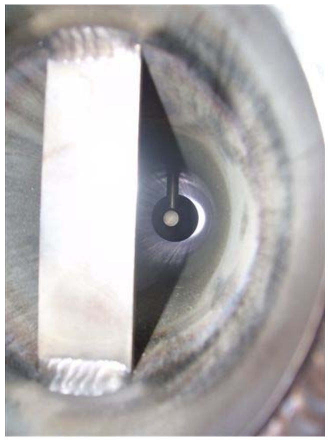

Fig 7. 4” flow meter & densitometer (flow left to right) and an internal view looking downstream.

point of the meter body length there are two pressure taps. These are the standard cone DP meter inlet and cone pressure taps. The upstream tap (to the left) is the point where the cone inlet pressure is read at the wall and the downstream tapping (2 ⅛” to the right to facilitate direct coupling of DP transmitters) is at the cones support bar location. It should be noted here that traditionally stand alone vortex meters have the pressure read (for the equation of state, or “ PVT” calculations) downstream of the bluff body. Hence the upstream pressure tap for the cone meter and the downstream pressure tap for the vortex meter are one and the same pressure tap in this design. Figure 4 also shows that the downstream pressure tap required for the DP meter diagnostics. Whereas this downstream pressure port does significantly increase the length of the flow meter it is evident that this 4” meter is not unreasonably long or heavy. Even with this extra 40% of length to accommodate the downstream pressure tapping the 3.826” ID meter with two components is still only 11D long at 42 inches (3.5 ft) long. If DP meter diagnostics were not required and the extra pressure tap not added, the vortex shedding bluff body and cone combination 4” schedule 80 mass flow meter would have been approximately 8D at 31 inches (2 ½ ft) long. The system had two DP transmitters added. The first measured the cone meters traditional DP and inlet pressure. The second measured the head loss. The recovered DP was inferred from equation 13. This kept the amount of instrumentation and cost to a minimum.

As a prototype instrument that was designed to predict volume and mass flow rates and also the fluid density it was necessary to test the meter over reasonable ranges. Therefore, the CEESI air flow tests had a turndown of approximately 14:1 (i.e. $6.4e6 \le Re \le 4.3e5$). Three nominal pressures / densities were set at 14 bar (16 kg/m^3), 27 bar (32 kg/m^3) & 41 bar (48 kg/m^3). The calibration of the standard vortex and traditional cone meter independent meters are shown in Figures 8 & 9. The cone DP meter expansibility was taken from Stewart [7]. Figure 8 shows the vortex meter K-factor (K_f) fitted best to a constant value. The constant K-factor fitted the data to an uncertainty of ±0.5%. There was no significant improvement in performance by fitting the K-factor to the Reynolds number. (This is not always the case for any given vortex meter over large turn downs.) With a constant K-factor for the vortex meter the volume flow rate was directly read by the vortex meter component. Figure 9 shows the vortex meters resulting volume flow rate prediction performance. Figure 10 shows the DP meter discharge coefficient fit. The constant discharge coefficient fitted the data to an uncertainty of ±0.5%. However, this could be further improved by fitting the discharge coefficient data to a linear fit with the Reynolds number. This linear line fitted the data to ±0.35%. The cone meters PLR value was a constant 0.424 ± 1%.

The most accurate method of predicting the mass flow rate and fluid density is to combine the vortex meters output with the traditional DP meters performance when the discharge coefficient

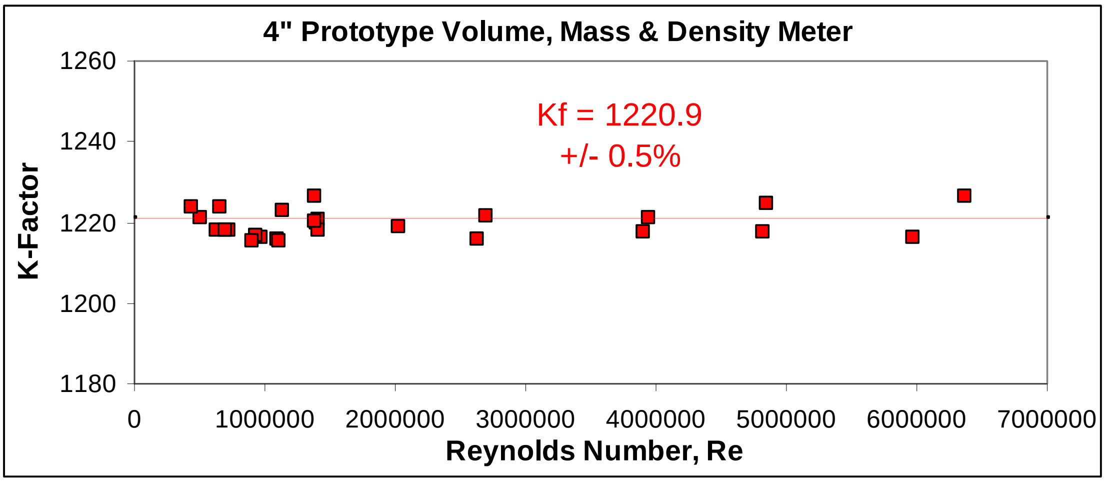

Fig 8. 4" prototype meters vortex K-factor, fitted as a constant.

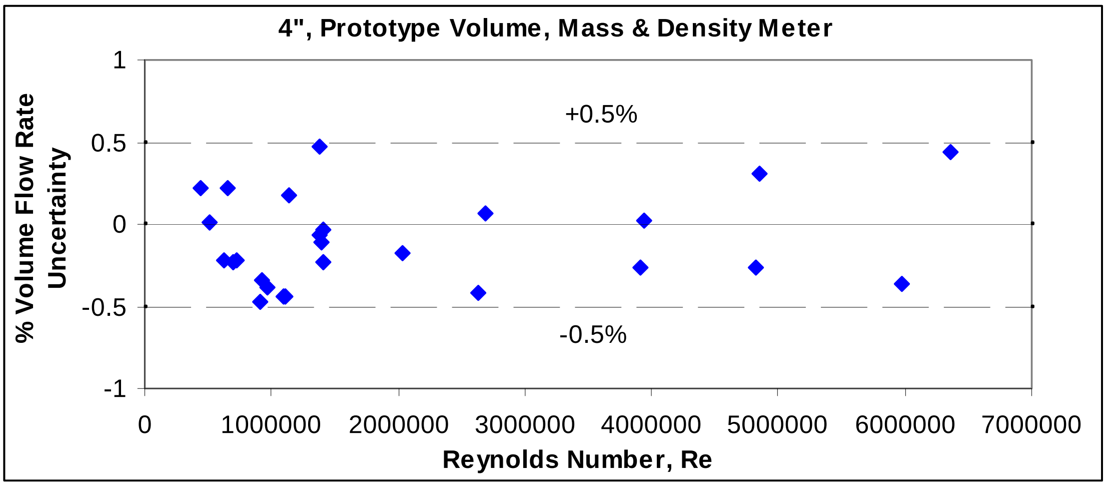

Fig 9. 4" prototype meters vortex meters volume flow rate prediction results.

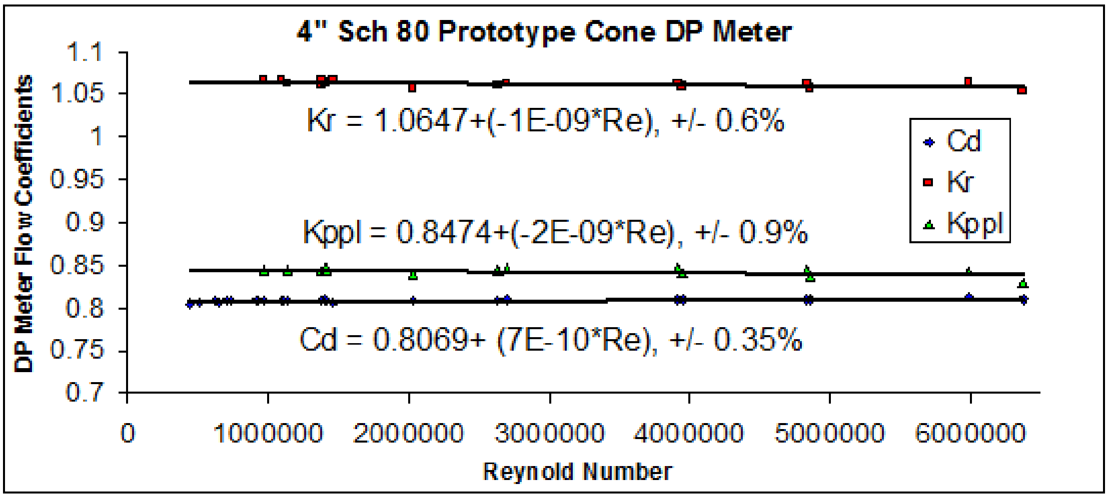

Fig 10. Cone DP meter flow coefficients as fitted to the Reynolds number.

is given by the Reynolds number data fit. The results of the iteration (on the Reynolds number) between the vortex and DP meter components are shown in Table 1 and in Figures 11 & 12. The volume flow rate prediction of the vortex meter has a 0.5% uncertainty. (All uncertainties quoted in this paper are for 95% confidence.) The mass flow rate prediction of the vortex meter has a 0.5% uncertainty. The density prediction has an uncertainty of 1%. (Note that in this case, for

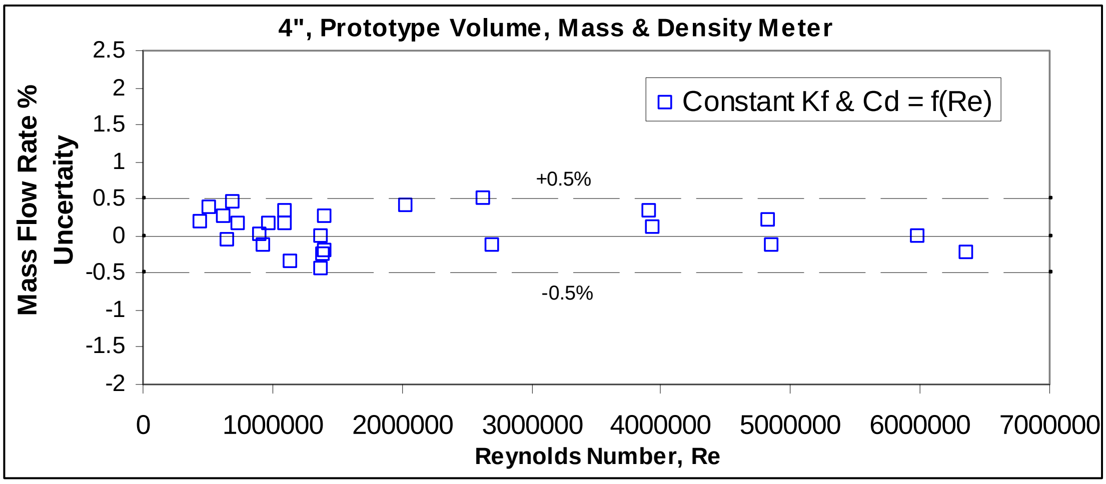

Fig 11. Mass flow rate results with constant K-factor & linear C_d fit.

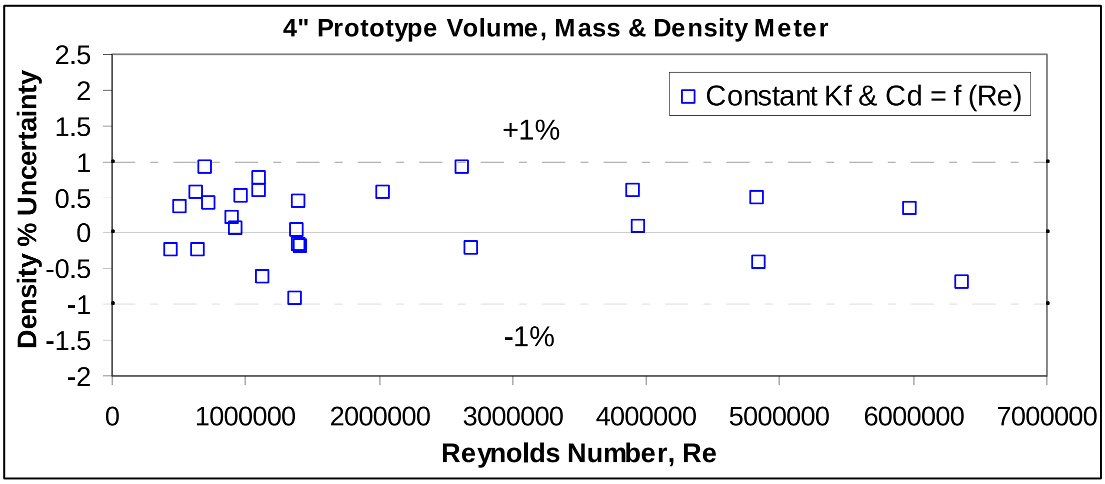

Fig 12. Density prediction results with constant K-factor & linear C_d fit.

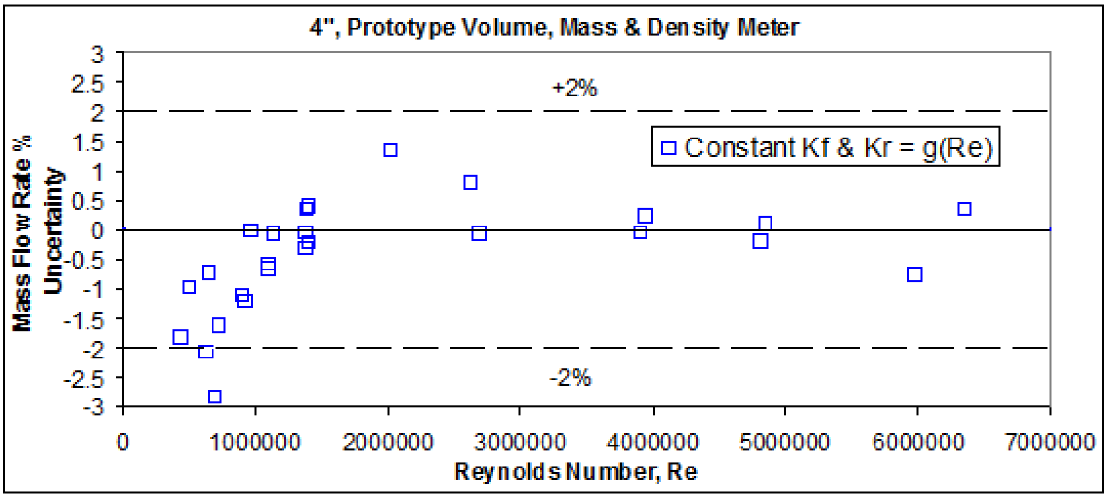

Fig 13. Mass flow rate results with constant K-factor & linear Kr fit.

gases the system requires to know the isentropic exponent and the gas viscosity. However, these values are usually readily available to meter operators. In this example approximations of a gas isentropic exponent of 1.4 and the gas viscosity estimate of 1.84e-5 Pa-s were held constant across all the flow conditions to give these results.)

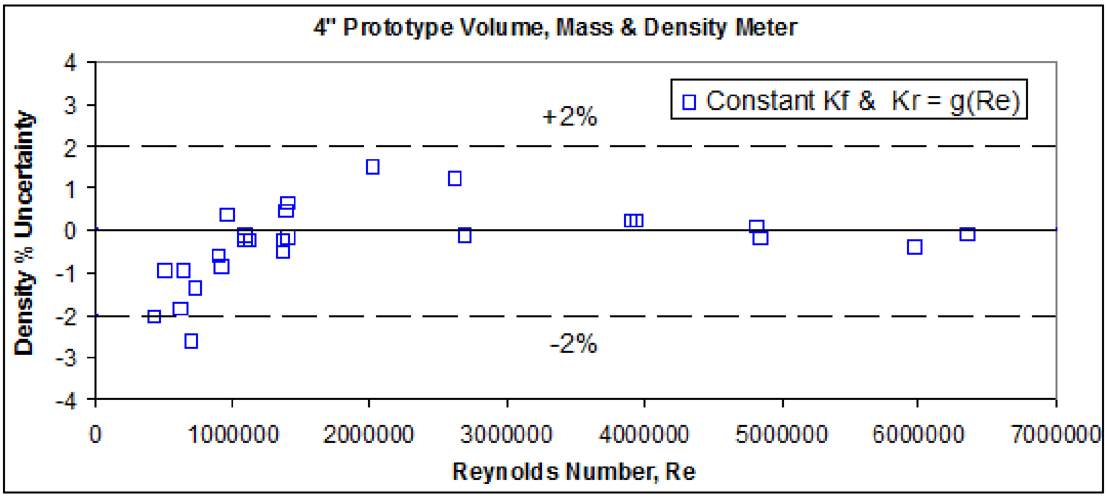

Fig 14. Density prediction results with constant K-factor & linear Kr fit.

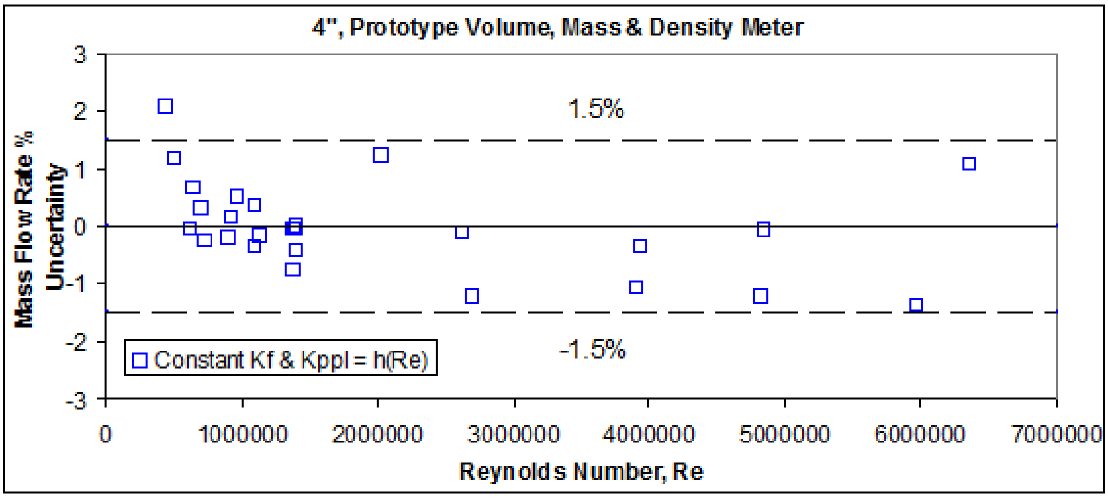

Fig 15. Mass flow rate results with constant K-factor & linear Kppl fit.

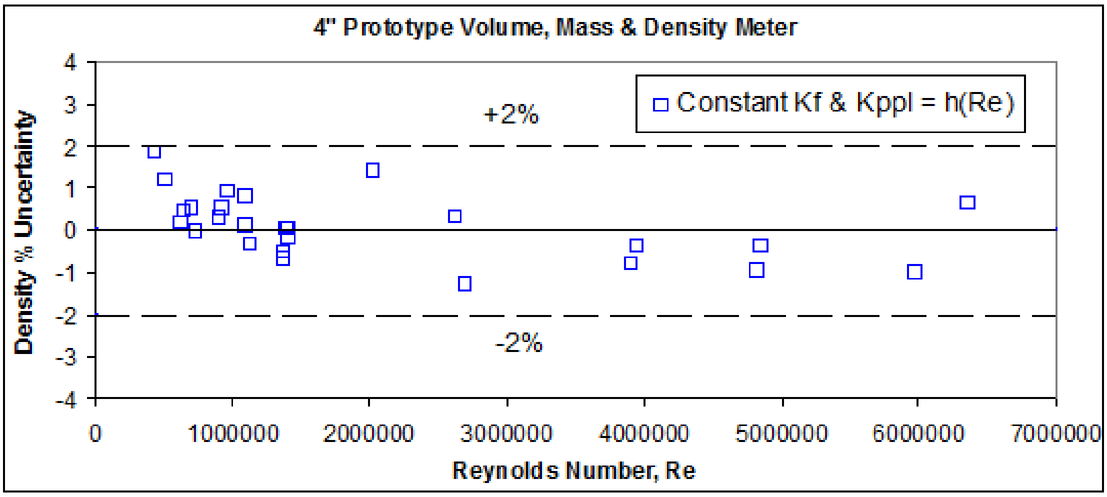

Fig 16. Density prediction results with constant K-factor & linear Kppl fit.

There are however two other methods of predicting the mass flow rate and the fluid density. The second is to compare the vortex meters volume flow rate with the cone meters expansion flow The third method is to compare the vortex meters volume flow rate with the cone meters PPL flow rate prediction. Again this is achieved by iteration of the Reynolds number. The results of this iteration are shown in Table 1 and in Figures 15 & 16. The volume flow rate prediction of the vortex meter has of course the same 0.5% uncertainty. The mass flow rate prediction of the vortex meter and expansion meter combination has a 1.5% uncertainty. The associated density prediction has again an uncertainty of 2%.

This system therefore produces one volume flow rate prediction via the vortex meter, and three mass flow rate predictions and three density predictions via the vortex meter and three DP flow equations. Therefore, if the system is operating correctly then all three volume flow rate to DP flow rate equation comparisons should give density values that are in agreement with their combined uncertainties. (Note, that the mass flow rate predictions are wholly dependent on the volume flow rate prediction of the vortex meter and the density predictions of the three iterations. Hence, the primary output for diagnostic comparisons are the density predictions.) It is common practice when comparing two associated uncertainties to take the root mean square of the two uncertainties as the combined uncertainties. However, to avoid false warnings in this diagnostic system it was decided here to allow a larger uncertainty of the sum of the two density uncertainties. Let us denote the vortex meter and traditional DP meter density prediction value as ρ_t , the vortex meter and expansion DP meter density prediction value as ρ_r and the vortex meter and PPL meter density prediction value as ρ_{PPL} . Therefore we can set the limits of normal operation.

Maximum allowable percentage difference between ρ_t & ρ_r (x%): x% = 1% + 2% = 3%

Maximum allowable percentage difference between ρ_t & ρ_{PPL} (y%): y% = 1% + 2% = 3%

Maximum allowable percentage difference between ρ_r & ρ_{PPL} (z%): z% = 2% + 2% = 4%

If the difference between any of these density prediction pairs exceeds these limits a warning exists to the user that the system may have a malfunction. Three examples are now presented as examples of this diagnostic system in operation. In actual use in industry many problems can occur. These include a flow being two-phase flow (i.e. a nominal gas flow where there is unexpected entrained liquids or a liquid flow where there are unexpected gas bubbles), contamination on the meter components, debris trapped at the meter components, physical damage to the meter due to impact from debris etc. In this first look it is not possible to investigate the prototype meters diagnostic systems response to these problems due to lack of experimental data. However, it is possible to investigate the diagnostic response of other common problems. If the diagnostics show these problems it is a reasonable assumption they will show many varied metering problems. One such problem we can investigate with the existing data is a problem with the communal pressure reading (due to various reasons, e.g. a blocked impulse line, or a drifting or poorly calibrated transmitter). Such a problem causes problems with the traditional PVT gas density and mass flow rate prediction for both independent meters. Another problem where we can simulate with existing data to show is the blocking of the low pressure port of the cone meter. In actual service, a blocked pressure port can signal the start of a serious problem which will affect all pipeline components, such as hydrate formation occurring in natural gas flow lines. A final problem that can be simulated to show the diagnostic response is the inappropriate extrapolation of flow meter calibrations. Such practice is unfortunately common in industry. A flow meters calibration is only valid across the Reynolds number range for which it was calibrated. However, it is common to calibrate meters with low Reynolds number ranges to save on calibration costs and then assume the calibration can be extrapolated to higher Reynolds numbers. Such practice has been known to cause significant metering errors.

							Const. Kf & Cd = f(Re)				Const. Kf & Kr = g(Re)				Const. Kf & Kppl = h(Re)			
Point No.	Actual Reynolds Number	Actual Vol Flow m3/s	Actual Mass Flow kg/s	Actual Gas Density kg/m3	Predict Vol Flow m3/s	Predict Vol Flow % Error	Predict Mass Flow kg/s	Predict Mass Flow% Error	Predict Gas Density kg/m3	Predict Gas Density %Error	Predict Mass Flow kg/s	Predict Mass Flow% Error	Predict Gas Density kg/m3	Predict Gas Density %Error	Predict Mass Flow kg/s	Predict Mass Flow% Error	Predict Gas Density kg/m3	Predict Gas Density %Error
1	2027500	0.177	2.83	15.98	0.18	-0.17	2.84	0.40	15.98	0.57	2.86	1.33	16.22	1.50	2.86	1.22	16.20	1.40
2	1377600	0.121	1.92	15.95	0.12	0.47	1.92	-0.45	15.95	-0.92	1.92	-0.05	15.87	-0.51	1.92	-0.04	15.87	-0.51
3	512160	0.046	0.72	15.75	0.05	0.01	0.73	0.38	15.75	0.36	0.72	-0.98	15.60	-0.99	0.73	1.17	15.94	1.17
4	1136000	0.101	1.60	15.80	0.10	0.18	1.59	-0.35	15.80	-0.62	1.60	-0.06	15.76	-0.24	1.60	-0.17	15.75	-0.34
5	650690	0.058	0.92	15.77	0.06	0.22	0.92	-0.06	15.77	-0.25	0.91	-0.75	15.62	-0.97	0.92	0.67	15.84	0.45
6	439660	0.039	0.62	15.75	0.04	0.22	0.62	0.19	15.75	-0.23	0.61	-1.84	15.43	-2.05	0.63	2.06	16.04	1.84
7	968790	0.086	1.36	15.79	0.09	-0.38	1.37	0.16	15.79	0.53	1.36	-0.03	15.85	0.36	1.37	0.51	15.93	0.89
8	1397300	0.124	1.97	15.83	0.12	-0.11	1.96	-0.24	15.83	-0.16	1.97	0.35	15.90	0.45	1.96	-0.06	15.84	0.05
9	1407200	0.061	1.97	32.23	0.06	-0.04	1.97	-0.21	32.23	-0.19	1.96	-0.22	32.17	-0.18	1.97	0.01	32.24	0.04
10	1404800	0.062	1.98	31.93	0.06	-0.23	1.98	0.25	31.93	0.45	1.99	0.39	32.12	0.62	1.97	-0.43	31.86	-0.20
11	732030	0.032	1.03	31.82	0.03	-0.22	1.04	0.18	31.82	0.42	1.02	-1.63	31.38	-1.41	1.03	-0.26	31.81	-0.04
12	629610	0.028	0.89	31.80	0.03	-0.22	0.89	0.25	31.80	0.56	0.87	-2.09	31.20	-1.87	0.89	-0.04	31.86	0.18
13	1100600	0.049	1.55	31.88	0.05	-0.43	1.56	0.17	31.88	0.59	1.54	-0.67	31.81	-0.23	1.55	-0.34	31.91	0.09
14	925630	0.041	1.31	31.85	0.04	-0.34	1.30	-0.12	31.85	0.05	1.29	-1.23	31.57	-0.89	1.31	0.16	32.02	0.51
15	2628800	0.114	3.67	32.30	0.11	-0.42	3.69	0.50	32.30	0.92	3.70	0.79	32.70	1.22	3.67	-0.12	32.40	0.30
16	3945000	0.170	5.51	32.37	0.17	0.02	5.51	0.11	32.37	0.08	5.52	0.23	32.44	0.21	5.49	-0.36	32.25	-0.38
17	4851300	0.209	6.77	32.41	0.21	0.30	6.76	-0.12	32.41	-0.42	6.78	0.10	32.35	-0.20	6.76	-0.08	32.29	-0.38
18	6363400	0.274	8.89	32.39	0.28	0.44	8.87	-0.23	32.39	-0.69	8.92	0.34	32.36	-0.10	8.98	1.06	32.59	0.61
19	906690	0.027	1.28	47.97	0.03	-0.47	1.28	0.01	47.97	0.21	1.27	-1.10	47.67	-0.64	1.28	-0.20	48.10	0.27
20	1103500	0.033	1.56	47.99	0.03	-0.44	1.57	0.34	47.99	0.75	1.55	-0.59	47.92	-0.15	1.57	0.35	48.37	0.79
21	1381200	0.041	1.95	47.98	0.04	-0.07	1.95	0.00	47.98	0.05	1.95	-0.32	47.86	-0.26	1.94	-0.78	47.64	-0.71
22	3910400	0.114	5.50	48.43	0.11	-0.26	5.52	0.33	48.43	0.58	5.50	-0.05	48.54	0.21	5.44	-1.07	48.04	-0.81
23	2695800	0.078	3.79	48.42	0.08	0.06	3.79	-0.13	48.42	-0.20	3.79	-0.08	48.35	-0.14	3.75	-1.22	47.80	-1.28
24	700750	0.021	0.99	47.98	0.02	-0.23	1.00	0.45	47.98	0.91	0.96	-2.85	46.72	-2.63	0.99	0.30	48.23	0.53
25	5979100	0.175	8.44	48.21	0.17	-0.37	8.44	-0.01	48.21	0.35	8.37	-0.77	48.01	-0.41	8.32	-1.37	47.72	-1.00
26	4826500	0.140	6.79	48.43	0.14	-0.27	6.81	0.22	48.43	0.49	6.78	-0.20	48.46	0.07	6.71	-1.23	47.96	-0.96

Table 1. All results from the calibration of the 4” prototype volume & mass flow meter and densitometer system.

4. Diagnostic System Worked Examples

4a. Vortex Meter Malfunction

The vortex meter is a sturdy reliable device. However like all equipment it can occasionally suffer malfunction for various reasons (e.g. erosive wear on the bluff body, contamination hampering the vortex shedding sensor equipment, keypad entry error of the calibrated K-factor, debris in the pipe trapped at the bluff body etc.). In this first example let us consider the first point in Table 1. The actual volume flow was known to be 0.177 m^3/s. Let us consider the scenario where the vortex meter has some unspecified problem and incorrectly predicts the volume flow rate at say, 0.15 m^3/s. In this example the cone meter operates correctly. The PVT gas density prediction is the correct 15.98 kg/m^3. Typically, industry would expect this density prediction to have an uncertainty no greater than 0.5%. However, when the vortex meters volume flow rate prediction is substituted into the three DP meter equations in turn (i.e. equation set 16a) the resulting density predictions are 22.37 kg/m^3 for the vortex & traditional DP meter combination, 22.52 kg/m^3 for the vortex & expansion DP meter combination and 22.43 kg/m^3 for the vortex & PPL meter combination. Inter-comparisons of the three density predictions internal to the system show that a vortex meters error produces approximately the same density error in all three prediction methods. Hence, no warning of any malfunction is available here.

Percentage difference between ρ_t & ρ_r : 0.26% i.e. < ±3% (x%) and no warning is given.
Percentage difference between ρ_t & ρ_{PPL} : 0.67% i.e. < ±3% (y%) and no warning is given.
Percentage difference between ρ_r & ρ_{PPL} : 0.41% i.e. < ±4% (z%) and no warning is given.

However, if an external density measurement exists with a PVT calculation or stand alone densitometer (as it typically is for stand alone vortex or DP meter use) the density value ($\rho_{external}$) is found to be 15.98 kg/m^3 ±0.5% which is distinctly different to the three meter system density predictions. These predictions are 40% in excess of the external systems density prediction. That is:

$$\rho_{external} \neq \left(\rho_t = \rho_r = \rho_{PPL}\right)$$

Furthermore, the DP meter can be shown to be okay as the three different systems agree with each other and the PLR is seen to be 0.423 compared to the calibrated value of 0.424, i.e. < 1% difference as required. Therefore, unlike when the vortex meter is installed as a stand alone device we can deduce that the vortex meter has an unspecified problem.

4b. Blocked Inlet Pressure Port (Affecting Both Meters)

In this example let us consider the case where contamination has blocked the inlet pressure port. Again, let us take point 1 in Table 1, shown in more detail in Table 2. For stand alone vortex meters or cone DP meters a blocked port where the pressure is read would mean an incorrect PVT calculation of the density and hence both types of meters would incorrectly predict density and mass flow rate.

ReyNo	P1 (Pa)	mg (kg/s)	DPt (Pa)	DPr (Pa)	DPhl (Pa)
2,027,500	1,358,819	2.827	15,276	8,816	6,459

Table 2. Actual test point used as baseline for diagnostic analysis of blocked inlet pressure tap.

If the inlet pressure port gets blocked the pressure in the impulse line remains set at whatever pressure it was when the blockage occurred. Let us imagine that before the actual conditions arrived at the values shown in Table 2 the inlet pressure port was blocked at the pressure of 1,355,000 Pa. Industrial flows considered steady can easily fluctuate by this pressure over a period of time. The actual gas density of air at 30^0C and 1,358,819 Pa is 15.7 kg/m^3, and the gas density found by PVT calculations when the inputs are 30^0C and 1,355,000 Pa is 15.65 kg/m^3. That is, the resulting PVT density calculation error due to the blockage is -0.31%. Such an error creates a mass flow rate prediction bias on both the vortex and cone meter mass flow rate predictions. This particular error is small but *it will significantly rise* if the line pressure significantly changes and the blockage remains unnoticed. The capability of noticing the blockage when it is causing as small an error as possible is therefore very desirable.

P1 (Pa)	Pt (Pa)	Pd (Pa)	DPt (Pa)	DPr (Pa)	DPppl (Pa)
1,355,000	1,343,543	1,352,359	11,457	8,816	2,641

Table 3. Artificial test if we had a blocked inlet pressure tap.

With the upstream pressure port blocked at 1,355,000 Pa but the other two pressure ports operating correctly the traditional DP is falsely read as 11,547 Pa and the PPL is falsely read as 2,641 Pa. Taking the difference of these two false readings to find the recovered DP causes the errors to cancel out and therefore the recovered DP is still read correctly at 8,816 Pa. This situation is shown in Table 3. The read PLR value is therefore 0.23 which is clearly not within the know cone DP meters calibrated PLR value of 0.424 ± 1%. This then, indicates that the DP meter has a problem.

Each of these three DP's are used in the three gas density predictions of equation set 16a. This produces density predictions we of 12.08 kg/m^3, 16.26 kg/m^3 & 6.6 kg/m^3 respectively. If a PVT density prediction system is in use its density prediction would be 15.65 kg/m^3, i.e. the inlet pressure port blockage induces a systematic error of -0.31%. (This is a bias imposed on the external density prediction system that will skew the normal 0.5% system uncertainty.) Therefore it is obvious when comparing this to the calculated values that something is wrong with the meter system. The first comparison is -22.8% low, the second is +3.9% high and the third is -57.8% low. In this situation it is very noticeable that the second density calculation, i.e. the vortex meter and expansion DP meter has a much smaller discrepancy than the other two density predictions.

$$\rho_{external} \approx \rho_r \neq \rho_t \neq \rho_{PPL}$$

This strongly indicates that there is a problem with the upstream pressure port. The two density calculations that use this port directly have large errors. The vortex and expansion DP meter combination does not use this port and only has a small error. However, as this density prediction has an uncertainty of 2% (see Figure 14) and the PVT density prediction has an uncertainty of 1%, if the system was operating correctly we will not see a difference between these density predictions greater than their summed uncertainties, i.e. 3% (or even the root mean squared uncertainty of 2.24%). Yet, we see a difference of +3.9%. This again, is actually proof that the problem is with the upstream pressure port. The absolute pressure of the pipe line usually dwarfs the differential pressures being produced by DP meters. In this case it is 1,358,819 Pa (and measured as 1,355,000 Pa) compared to an actual traditional DP of 15,276 Pa (measured here erroneously as 11,457 Pa). That is the traditional DP is only 1.1% of the absolute pressure. Therefore, a small error in the inlet pressure reading causes a small error in the PVT gas density but a large error in the read DP's. The vortex meter and expansion DP meter prediction has a much smaller problem than the other two density prediction methods but is still just outside the PVT calculation uncertainty limits. This is because the small inlet pressure port error induces a small PVT calculation error. This scenario is indicative of a blocked inlet pressure port.

As we have derived that the vortex with the expansion cone meter density prediction is correct we know that the real flow conditions are within the uncertainties of the vortex meter with the expansion cone meter system, i.e. 0.1776 m^3/s ±0.5%, 16.26 kg/m^3 ±2%, and 2.871 kg/s ±2.1%. We can now substitute this mass flow rate and density prediction into the traditional DP meter equation (i.e. equation 6) and derive the only unknown, i.e. the *actual* differential pressure, ΔP_t. Such an iteration on equation 6 produces an actual inlet pressure estimate of 1,358,997Pa compared to the real pressure of 1,358,819Pa. We also get an actual traditional DP of 15,454Pa compared to the real traditional DP of 15,276Pa, i.e. a 1.17% difference. The difference between the actual and read DP was -25%.

If either the vortex meter or the cone meter were stand alone meters and the pressure port was blocked there would be no conventional way of showing an error exists. However, with the meters in series and a PVT density calculation (which was erroneous!) we have diagnosed that:

a) The metering system has a problem.
b) The vortex meters bluff body is probably operating correctly.
c) The DP meter is definitely not operating correctly.
d) The inlet pressure port is blocked.
e) The inlet pressure port is blocked at an artificially lower pressure of approximately 3,997 Pa.
f) Even though the system has a problem we still know the actual volume flow rate is 0.1776 m^3/s ±0.5%, the actual density is 16.26 kg/m^3 ±2% and the actual mass flow rate is 2.871 kg/s ±2.1%.

Hence, if the system has a PVT density estimation there are qualitative and quantitative diagnostics. If no PVT density estimation is available then the system can offer qualitative diagnostics. If a density prediction difference is greater than the maximum difference allowed (i.e. x%, y% and z%) then a problem with the meters health is indicated. In this case we have the following results.

Percentage difference between ρ_t & ρ_r : -44.8% i.e. > ±3% (x%) and <u>a warning is given</u>.
Percentage difference between ρ_t & ρ_{PPL} : 34.5% i.e. > ±3% (y%) and <u>a warning is given</u>.
Percentage difference between ρ_r & ρ_{PPL} : 143.9% i.e. > ±4% (z%) and <u>a warning is given</u>.

Hence, if a vortex meter or a DP meter operated alone and their pressure port was blocked there would be no traditional diagnostics to warn of the problem and the meter mass flow rate output would be believed by the operator. In this case an induced density bias of -0.31% would not be noticed. However, if the vortex meter and the cone meter are in series there is a very sensitive check to show if the system is serviceable.

4c. <u>Blocked Low Pressure Port on the Cone Meter</u>

Let us consider a case where the DP meter alone has a malfunction - contamination has blocked the low pressure port (in the cone element). This issue is different from the second example as it does not affect the traditional PVT calculation of the gas density and will not affect the mass flow rate prediction of the vortex meter in any way. In this case only the cone meter is affected. However, if a traditional cone meter was installed as a stand alone meter there would be no diagnostics to indicate the problem.

Again the actual air flow test point condition considered is the first test condition as shown in Table 1. However, here we have a blockage at the cone element pressure tap. Let us say the low pressure port which should be at 1,343,543 Pa is actually blocked with a pressure of

1,343,919 Pa, i.e. a difference of 375.5Pa (or approximately 1.5 "WC). If the system has a gas density prediction that uses the PVT system, the gas density prediction will be correct at 15.98 kg/m^3 as the upstream pressure tap is not blocked. However, the traditional flow rate prediction will be erroneous.

In this example the traditional DP is 14,900 Pa (instead of the correct 15,275.5 Pa). The PPL reading is not affected and is correctly read at 6,459.5 Pa. The recovered DP is read in error at 8,440.6 Pa. We see the measured PLR is found to be 0.4435 which is +2.25% from the calibrated correct value of 0.424 ±1%. Therefore, this strongly indicates that the DP meter has a problem and the vortex meter can be assumed to be correct until the DP meter is examined.

When equation set 16a is applied to produce three density predictions we get 15.68 kg/m^3, 15.57 kg/m^3 & 16.21 kg/m^3 respectively. If we are using an external density calculation we would get a prediction of 15.98 kg/m^3. The allowable difference between the external density prediction compared to each of these density predictions is the sum of the uncertainties. Therefore we have the following results.

Maximum allowable percentage difference between $\rho_{external}$ & ρ_t (a%): x% = 0.5% + 1% = 1.5%
Maximum allowable percentage difference between $\rho_{external}$ & ρ_r (b%): y% = 0.5% + 2% = 2.5%
Maximum allowable percentage difference between $\rho_{external}$ & ρ_{PPL} (c%): z% = 0.5% + 2% =2.5%

Percentage difference between $\rho_{external}$ & ρ_t: -1.8%% i.e. > ±1.53% (x%) warning given.
Percentage difference between $\rho_{external}$ & ρ_r: -2.60% i.e. > ±2.5% (y%) warning given.
Percentage difference between $\rho_{external}$ & ρ_{PPL}: +1.40% i.e. > ±2.5% (z%) warning not given.

Two of the three density predictions indicate a problem. It is the vortex and PPL meter combination that predicts a density that when compared to the external density prediction agrees to within the uncertainty limits. This indicates that it may be the DP meters low pressure tap that has the problem as the only correct result is the only comparison that does not use the low pressure tap. In this case we can then trust the vortex & PPL meter outputs of 0.1776 m^3/s ±0.5%, 16.21 kg/m^3 ±2%, and 2.862 kg/s ±2.1%. Furthermore, if we substitute these correct mass flow rate and density values into equation 6 we get a predicted actual traditional DP of 15,406 Pa. That is a difference of 131 Pa (or approximately ½ "WC) compared to the uncorrected difference of 375 Pa (or 1.52"WC). Therefore, we have found that there is a problem with the traditional DP measurement and that the actual pressure of the flow at the low pressure point is approximately 1,343,413 Pa (i.e. inlet pressure 1,358,819 Pa – calculated actual DP 15,406 Pa). However, we have found that the low pressure port is blocked and the pressure in the impulse lines is set at an artificially high value of approximately 1,343,919 Pa (i.e. inlet pressure 1,358,819 Pa – read DP 14,900 Pa), i.e. 375 Pa too high.

If the cone meter was a stand alone meter and the low pressure port was blocked there would be no conventional way of showing an error exists or estimating the scale of the error. However, with the meters in series and an external density calculation we have diagnosed from the available system readings and the hydraulic theory rules of vortex meters and DP meters that:

a) The metering system has a problem.
b) The vortex meters bluff body is probably operating correctly.
c) The DP meter is definitely not operating correctly.
d) The low pressure port is blocked.

e) The low pressure port is blocked at a higher pressure than exists in the flow and the pressure trapped in the impulse line is approximately 375Pa (i.e. 1.5"WC) higher than the actual flow pressure.
f) Even though the system has a problem we still know the actual volume flow rate is 0.1776 m^3/s ±0.5%, the actual density is 16.21 kg/m^3 ±2% and the actual mass flow rate is 2.862 kg/s ±2.1%.

If no external density prediction exists and the fluid density is found by the system alone then the diagnostics are from inter-comparison of the three density predictions. As it's the same fluid through the same system the three density predictions must be very close. In this case we have:

Percentage difference between ρ_t & ρ_r : -0.72% i.e. < ±3% (x%) and no warning is given.
Percentage difference between ρ_t & ρ_{PPL} : 3.36% i.e. > ±3% (y%) and a warning is given.
Percentage difference between ρ_r & ρ_{PPL} : -3.95% i.e. < ±4% (z%) and no warning is given.

Therefore, we can see that a problem exists, if only through one of the three density comparisons. We also see that a problem exists through the comparison of the measured to calibrated PLR values. Hence comparing the traditional DP meter to the vortex meter or the other DP's read across the cone meters body allows a diagnostic warning that would not exist for a standard stand alone DP meter.

4d. Inappropriate Extrapolation of Calibrations

It is necessary to calibrate all cone meters (Hodges [5]) and vortex meters across their flow conditions. More precisely this means it is necessary to calibrate these meters across the Reynolds number range (or "turndown") for which they will be used. Hence, it is necessary to calibrate this combined vortex meter and cone meter system.

Unfortunately it is common practice in industry to calibrate meters at low Reynolds numbers and then apply these calibrations at much higher Reynolds numbers. This is often done due to time and financial restraints. However, this extrapolation of calibrations can produce systematic errors in the flow rate predictions. Figure 10 shows the prototype mass meter systems cone meter calibrations. (Note that typically only the discharge coefficient data is recorded.) The turndown is approximately 14:1 (i.e. 6.4e6 ≤ Re ≤ 4.3e5). A linear data fit was produced showing the discharge coefficient as a function of the Reynolds number. However, if an operator had chosen to calibrate the meter at lower Reynolds numbers only (say Re < 1.5e6) then a constant value discharge coefficient could be considered appropriate. Figure 17 shows the contrast of the actual data and linear fit and the extrapolation of a low Reynolds number constant discharge coefficient fit. At the lower Reynolds numbers the constant and linear fits agree. However, as the Reynolds number increases and the constant fit is extrapolated it clearly under predicts the discharge coefficient. In service such a problem would cause the under-reading of the flow rate. In this particular example, at the highest Reynolds number tested the extrapolated constant discharge coefficient prediction is approximately -0.5% below the linear fits discharge coefficient prediction and -0.35% from the data point. Therefore, in this case if this was a stand alone cone meter with an extrapolated calibration the meter would have a systematic negative error of approximately -0.35%. However, this meter is not a stand alone cone meter. It is part of the prototype mass meter, i.e. the vortex meter is upstream.

The vortex meter was found to have a constant K-factor across the turndown of the calibration. Hence, in this case extrapolating the vortex meter performance should not produce a bias. From

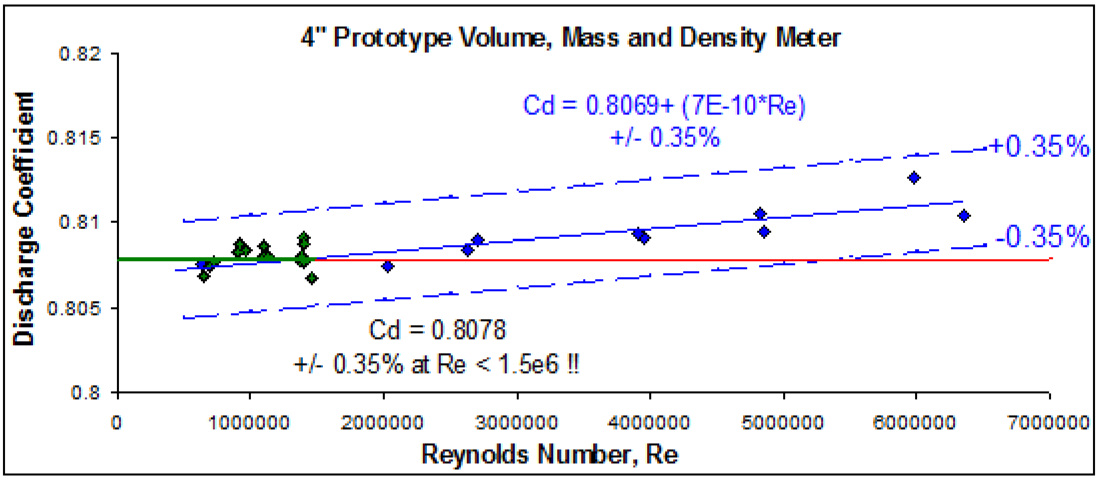

Fig 17. Detailed calibration data for 4" prototype mass meter cone DP meter section.

a diagnostic perspective inter-comparing the two meters in series when the calibrations have been extrapolated can indicate that the system has a problem. At Re<1.5e6 the constant value calibration fits on the system were a vortex meter K-factor of 1220.9 (±0.5%, i.e. the same as the full calibration), discharge coefficient of 0.8078 ±0.5%, expansion coefficient of 1.064 ±0.5%, and a PPL coefficient of 0.845 ±0.5%. Let us now extrapolate these calibrations to point 18 of Table 1 that has a Reynolds number of 6.4e6 Pa. The difference in the four calibration coefficients between the low Reynolds number constant data fit and the linear fit at this high Reynolds number is 0% for the vortex meter K-factor, -0.44% for the discharge coefficient, +0.54% for the expansion coefficient and +1.24% for the PPL coefficient. Hence, if this cone meter was a traditional stand alone meter at a Reynolds number of 6.4e6 with an *extrapolated* discharge coefficient it would have a systematic flow rate bias of -0.44%. A traditional DP meter has no way of diagnosing such a problem. However, when we compare the three meter density predictions to either an external density prediction or if this is not available to each other we see that in both cases a warning of some problem is produced.

Percentage difference between $\rho_{external}$ & ρ_t : -1.51%% i.e. > ±1.5% (x%) <u>warning given</u>.
Percentage difference between $\rho_{external}$ & ρ_r : +0.98% i.e. > ±2.5% (y%) no warning given.
Percentage difference between $\rho_{external}$ & ρ_{PPL} : +3.15% i.e. > ±2.5% (z%) <u>warning given</u>.

Percentage difference between ρ_t & ρ_r : 2.5 % i.e. < ±3% (x%) and no warning is given.
Percentage difference between ρ_t & ρ_{PPL} : 4.7% i.e. > ±3% (y%) and <u>a warning is given</u>.
Percentage difference between ρ_r & ρ_{PPL} : 2.1 % i.e. < ±4% (z%) and no warning is given.

5. Conclusions

Stand alone vortex meters and cone meters are both sturdy and reliable flow meters. However, there are many potential problems that can affect their performances and are difficult to diagnose when they are stand alone devices. When installed together they make a simple but reliable mass and volume flow meter and a densitometer. This initial 4" prototype meter showed the volume and mass flow rates could be predicted to 0.5% uncertainty while the gas density could be predicted to 1% uncertainty. Predicting the gas density also gives redundancy to an external density calculation system. Furthermore, with the addition of a downstream pressure tap the DP meter can have three flow rate equations thereby adding extra redundancy to this metering system.

This also allows substantial diagnostics to exist via inter-comparison of all the sub-systems in such a metering system.

The disadvantages of this proposed system is the extra weight, volume, instrumentation and cost. Effectively, in its simplest form the user would be buying two meters instead of one. Furthermore, the downstream pressure tap on the cone meter adds to the over all foot print of the meter. However, it should be noted that the only industrial grade mass flow rate and density meter designs currently on the market are Coriolis meters. These are known to be reliable and accurate but also big and heavy relative to the pipe size and rather expensive. They are also not known for particularly accurate density measurement of low pressure low flow rate gases. Therefore, this prototype mass meter described in this paper is not unrealistically large, heavy or expensive in comparison.

Currently vortex meters require a vortex shedding sensor, a pressure transmitter, a thermocouple and a flow computer. DP meters require a pressure transmitter, a DP transmitter, a thermocouple and a flow computer. In some cases one smart transmitter replaces the pressure transmitter and the DP transmitter. Hence, it is possible to combine the flow computer and the pressure transmitter of both instruments. Therefore the amount of instrumentation needed is not much greater for the hybrid system. It would need a vortex shedding sensor, one smart transmitter (reading the pressure and traditional DP meter), an extra DP transmitter (to read the PPL), a thermocouple and a flow computer. In fact the thermowell is only needed if the PVT gas density prediction is to be used.

The design discussed here is a first stage design. It is suspected that a considerably more compact hybrid system could be produced. Investigations are currently under way to develop a patent pending hybrid system where the vortex meter and cone meter are blended into the same structure. The bluff body may be integral to the cone meters support bar. It may be possible to reduce the downstream pressure tap length hence further reducing the meters overall length and weight.

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