Mass Flow Metering – An Alternative Approach

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Abstract
Most flow meter designs are volume flow meters that are wholly dependent on the independent fluid density prediction being available and trustworthy for their mass flow prediction to be accurate. Mass flow meters can be defined as flow meters which do not need the fluid density supplied from an external source in order to meter the mass flow rate. With no external density prediction required there is an advantage to direct mass flow metering. There are significantly fewer mass meter designs than volume meter designs. There is the Coriolis mass meter used across industry and niche markets for the thermal mass meters and laboratory sonic nozzles for gas flow. However, industry has long had an alternative generic mass flow meter design, it has just never been developed into a product. The mass flow meter concept of combining density sensitive meter technology (e.g. a DP meter) with density insensitive meter technology (e.g. turbine or vortex meters) to produce a mass flow, volume flow and density output has been about for sixty years. However, the various prototypes developed over the years have all had practical difficulties. Most hybrid designs suffered from the two meter technologies interfering with each other, and having different flow ranges. VorTek Instruments and DP Diagnostics have now overcome these obstacles. The design of a hybrid vortex and cone DP meter system installed in one compact spool has now been proven to operate as a mass flow meter, volume flow meter and densitometer, without any external fluid density input being required. The cone DP meter sub-system also has the latest DP meter diagnostic package ("Prognosis") developed by DP Diagnostics. In this paper, data from meters tested at CEESI with air and with water are shown. Data from one of the commercial meters on site will also be shown. A 4" mass meter was installed on an oil truck in the US where oil density was not always precisely known. The data from this meter will be presented compared to the truck loading reference meter.

1. Introduction

Gas flow must ultimately be metered by mass flow. A steady gas flow down a pipeline has a constant gas mass flow rate but a volume flow rate that varies with thermodynamic conditions. It can be advantageous to meter a fluid's mass flow rate directly rather than requiring an external fluid density prediction to combine with a volume meter's volume flow rate output. Such meter designs tend to be described as 'mass flow meters'. The development of a simple, robust and compact gas mass flow meter concept is described here.

Although sonic nozzles and thermal mass meters are good mass flow meters for select niche applications, the Coriolis meter is widely considered to be the *only* practical low uncertainty general use industrial mass flow meter available. However, an alternative gas mass flow meter design has existed for decades, i.e. the concept of cross referencing the outputs of a density sensitive and density insensitive flow meters (Boden [1]). This allows the prediction of the fluid density, volume flow rate & mass flow rate without any fluid density information being required from an external source.

The two meters could be placed in series or a hybrid meter design that blends the two separate technologies into one meter body could be considered. There have been multiple improvements and independent "re-inventions" of this concept, and yet the concept remains obscure and an academic curiosity. There appears to be three main reasons for this:

- It was many years after Boden's initial invention before computer power made it practically and economically viable,
- Two meters in series can be perceived as a heavy & expensive "contraption" meaning that it is a hybrid design that is practical,
- Such hybrid meter designs have practical complications.

In this paper the concept is described along with a solution to the practical design problem that blighted other hybrid meter designs. A new hybrid design consisting of a DP meter & a vortex meter is introduced. The DP meter sub-system can be fully equipped with the modern DP meter diagnostic system 'Prognosis'. Data from test meters and the first commercial meter will be shown.

2. History of the Boden Mass Meter Concept

Boden [1] stated that cross referencing density sensitive and density insensitive meters in series produces a density prediction along with a volume and mass flow rate predictions. Boden placed a turbine (density insensitive) meter in the throat of a Venturi (density sensitive) meter to produce a mass meter (see Figure 1). Pfrehm [2] considered the adverse effect of a turbine meter in a Venturi throat to excessive and modified this design (see Figure 2). However, the Pfrehm design still produces a highly unorthodox Venturi meter with questionable performance.

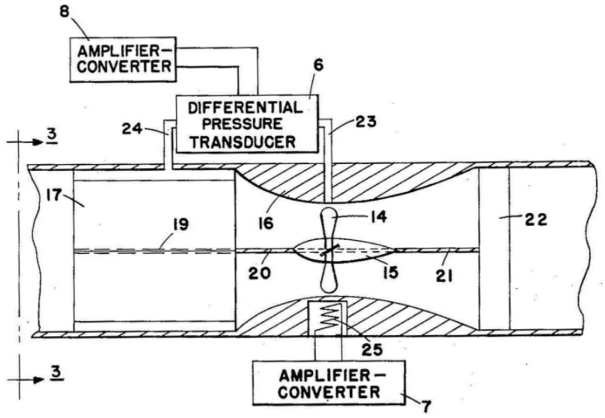

Fig 1. Boden Turbine + Venturi Meter

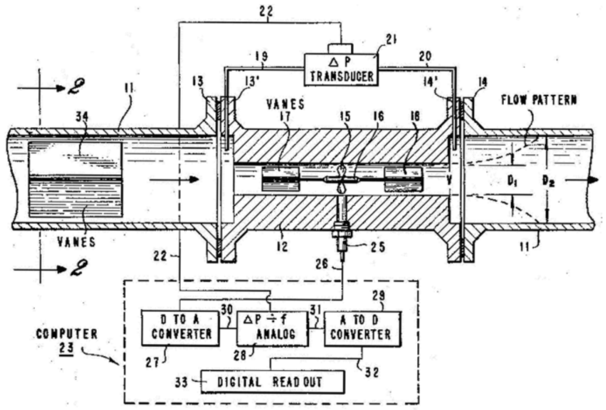

Fig 2. Pfrehm, Turbine + Modified Venturi Meter

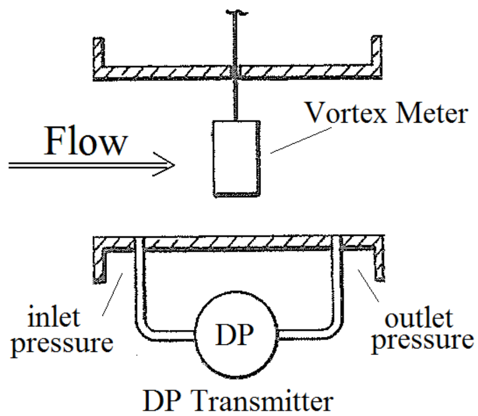

Fig 3. Lisi's Vortex Meter + DP Meter

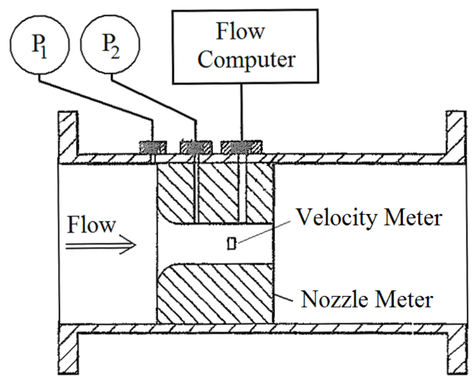

Fig 4. Mottram's Vortex Meter + Nozzle Meter

Lisi [3] suggested a vortex (density insensitive) meter and an orifice (density sensitive) meter in series. Lisi then dispensed of the independent orifice (DP) meter by reading the DP created across the vortex meter bluff body, i.e. using the vortex bluff body as a DP meter primary element (see Fig 3).Mottram [4] placed a vortex (density insensitive) meter in an *extended* throat of a nozzle (density sensitive) DP meter (see Fig 4). Vortex meters operate at peak performance at moderate to high flow velocities. Hence, Mottram placed the vortex meter in the DP meter throat to increase the fluid velocity at the vortex meter and achieve enhanced vortex meter performance.

Although Boden first described the concept in 1956 and there has been sporadic academic developments up until now no such device had been successfully marketed. This raises the obvious under lying question of why? One issue is that much of the research was at a time when the computing power required was not practically available. It was a good theoretical idea but difficult to implement in practice. Furthermore, the primary idea to put separate meters in series is more expense, more maintenance, more footprint etc. than standard meters. A single hybrid meter is more attractive. However, whereas combining density sensitive & density insensitive flow meters into a single hybrid meter design is theoretically sound, in practice it can suffer from two practical limitations. These are:

- In practice the two meters performances are equally important for the concept to work, but the suggested designs tend to choose one meter as the primary meter, with the other meter's performance being compromised. E.g. in Figs 1, 2, & 4 the DP meter's have other meters in their throat's adversely affecting their performance.
- In practice the two meters flow ranges must be similar and over lapping for the concept to work, but the suggested designs tend to produce two metering sub-systems (i.e. the density sensitive and insensitive meters respectively) with a mismatch in flow ranges, thereby compromising the performance of the overall system.

Modern day computers easily have the power to cross reference two meter outputs in real time. Therefore, if a hybrid design can be produced such that the two meter's operate together across the same flow range both to reasonable accuracy, then the concept will work successfully. The 'trick' to a successful hybrid design is finding a combination of density insensitive and density sensitive flow meters that can be combined into a hybrid design without significantly affecting either meters performance, while allowing each meter to be independently 'sized' to operate well across the same flow range. This has now been achieved with the combination of a vortex (density insensitive) meter in combination with a cone DP (density sensitive) meter.

3 Flow Metering Concept

A vortex meter operates by exposing a bluff body to the fluid stream. Vortices shed from the bluff body in a cyclic fashion (see Figure 5). This series of downstream vortices is called a “von Karman vortex street”.. The vortex shedding frequency has a nominally linear relationship with the average fluid velocity. Hence, reading the vortex shedding frequency allows the average flow velocity to be found. Equation 1 is the generic vortex meter volume flow rate equation.

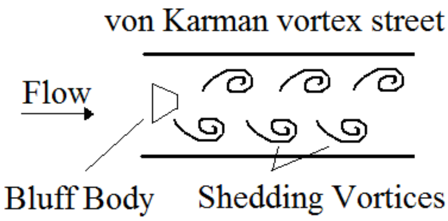

Fig. 5. Cyclic vortex shedding from a bluff body.

$$\dot{Q} = A\frac{f}{K_v} \text{ ---- (1)}$$

$\dot{Q}$ denotes the volume flow rate (at line conditions), “A” is the cross sectional area of the meter inlet, ‘f’ is the measured frequency of vortex shedding, & “K_v” is the vortex meter “K-factor” (which is usually found by calibration). As the vortex meter K-factor (K_v) is either set as constant or data fitted to the average gas velocity the vortex meter volume flow rate prediction is independent of the fluid density (ρ).

If the vortex meter operator chooses to plot K factor against velocity (U_1) the resulting calibration fit (function “f_1” as shown in Equation 2), means that an iteration on the average velocity is required to solve for volume flow rate, i.e. Equation 3 requires an iterative solution. Equation 4 gives the mass flow rate (m).

$$K_v = f_1(U_1) \text{ --- (2)}$$

$$\dot{Q} = \frac{f}{K_v} = \frac{f}{f_1(U_1)} \text{ --- (3)}$$

$$m = \rho Q \text{ --- (4)}$$

Therefore, in order to predict the mass flow rate, the stand-alone vortex meter requires the fluid density (ρ) from an external source.

Figure 6 shows a sketch of a cone meter. Cone meters are generic DP meters and operate according to the same physical principles as other DP meters. The beta of a DP meter (cone meter inclusive) is defined as equation 5, where ‘A_t’ is the minimum cross section (or ‘throat’) area. The velocity of approach (E) is calculated by equation 6. The expansibility for gas flow is

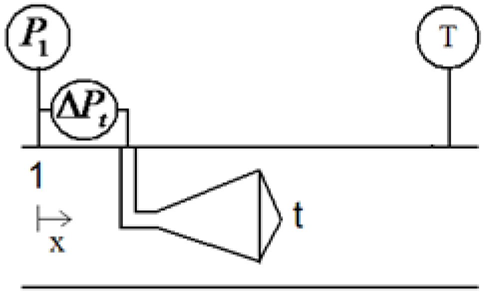

Fig 6. Sketch of a Cone Meter

calculated by equation 7. Here κ denotes the gas isentropic exponent, while P_1 & ΔP_t are the inlet and differential pressures respectively. For liquid flow this value is unity. The discharge coefficient (C_d) is found by calibration, and is typically either set as constant or as some curve fit to the Reynolds number (see equation 8). The Reynolds number is calculated by equation 9, where μ is the fluid viscosity. The DP meter volume and mass flow rate calculations are shown here as equations 8 & 9.

$$\beta = \sqrt{A_t/A} \text{ --- (5)} \qquad E = \frac{1}{\sqrt{1-\beta^4}} \text{ --- (6)}$$

$$\varepsilon = 1 - \left\{ \left(0.649 + 0.696\beta^4\right)\frac{\Delta P_t}{\kappa P_1} \right\} \text{ -- (7)}$$

$$C_d = f(\mathrm{Re}) \text{ -- (8)} \qquad \mathrm{Re} = \frac{4m}{\pi\mu D} = \frac{4\rho Q}{\pi\mu D} \text{ -- (9)}$$

$$Q = EA_t\varepsilon C_d\sqrt{\frac{2\Delta P_t}{\rho}} \text{ -- (10)}$$

$$m = \rho Q = EA_t\varepsilon C_d\sqrt{2\rho\Delta P_t} \text{ --- (11)}$$

The equation set 5 thru 11 indicates that if the discharge coefficient is described as a curve fit to Reynolds number (as it often is) the calculation of either the DP meter volume or mass flow is an iterative solution on that respective flow rate. Notably, for a DP meter to find the volume or mass flow the meter user must supply the fluid density. If the discharge coefficient is set to the Reynolds number, the user will also need to know the fluid viscosity. In the case of a gas flow the user will need to know the isentropic exponent. However, in practice it is relatively easy to estimate the viscosity and isentropic exponent for many fluids at an approximately known pressure and temperature[1]. Furthermore the flow rate prediction tends to be rather insensitive to these two

[1] This discussion excludes the very specialist niche discipline of flow metering highly viscous ‘heavy oil’ at very low Reynolds numbers (<< 2,000).

fluid property inputs. This is not true of the density. Density can be more difficult to estimate, and the flow rate calculation is sensitive to the value used. Like vortex meters, standalone DP meters are reliant on an accurate prediction of fluid density being supplied to the flow rate calculation.

$$Q_{vortex} = EA_t \varepsilon C_d \sqrt{\frac{2\Delta P_t}{\rho}} \quad \text{--- (10a)}$$

$$\mathrm{Re} = \frac{4\rho Q_{vortex}}{\pi \mu D} \quad \text{--- (9b)}$$

However, if a density insensitive volume meter (e.g. a vortex meter) was in series with a DP meter the resultant volume flow rate prediction (Q_{vortex}) would be available for use in the DP meter volume flow rate calculation (i.e. see equation 10a) and the associate Reynolds number calculation (see equation 9b). Therefore, the only unknown in equation set 10a, 9b and 8 becomes the fluid density. If the discharge coefficient is set to a constant value it is directly calculated from equation 10a. The density is found by iteration of this equation set. This iteration produces an associated mass flow prediction meaning the combination of the vortex and cone meter has produced a mass & volume flow rate prediction with a density prediction.

4 A Hybrid Vortex / Cone Mass Meter Design

The design of a hybrid vortex / cone meter took several iterations as Vortek Instruments & DP Diagnostics learned from trial & error. This learning process is described by Sanford et al [5]. Figure 7 shows a sketch of the final design prototype. Figure 8 shows a photograph of the 4" 0.563β prototype meter under air flow test at CEESI. The cone element was one diameter downstream of the supporting vortex meter bluff body structure. For simplicity this prototype meter was a flangeless 'wafer style' meter. The inlet & downstream diagnostic pressure taps (see Section 6) were on the upstream and downstream pipes respectively. The cone extended into the downstream pipe. Unlike Figure 7 the actual meter produced (Figure 8) had the cone low pressure port located at 180^0 to the vortex shedding sensor and the vortex meter head. In practice it was found that this produced a less congested design without compromising performance.

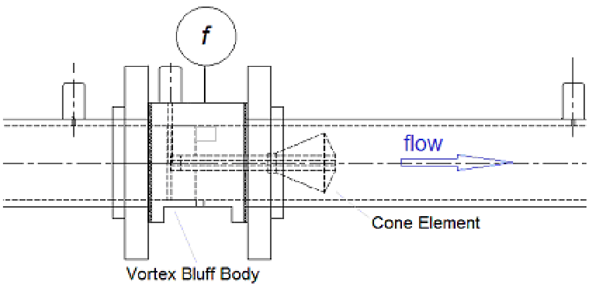

Fig. 7. Fourth Hybrid Vortex / Cone DP Meter Design

Fig 8. The Prototype Mass Meter Installed at CEESI.

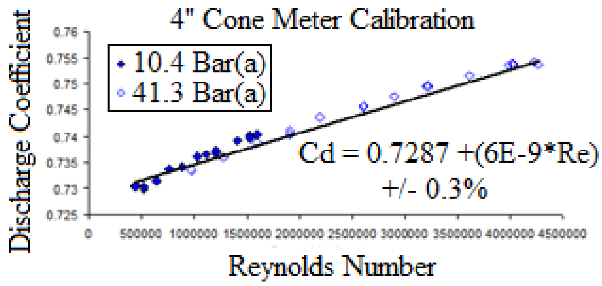

Fig 9. Cd Calibration of the Cone Meter Sub-System.

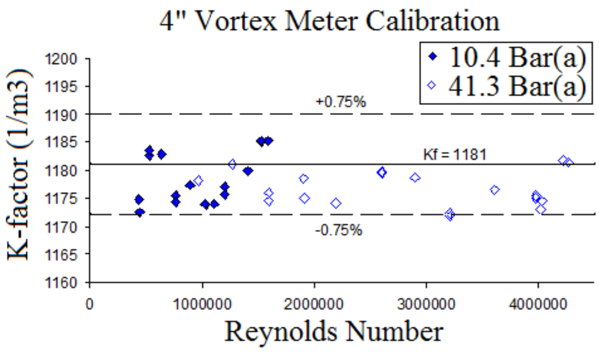

Fig 10. Kf Calibration of the Vortex Meter Sub-System.

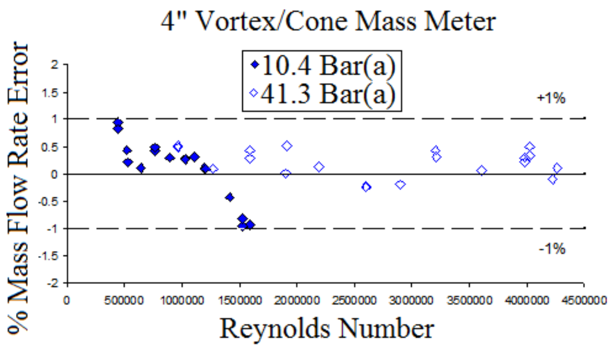

Fig 11. 4" Mass Meter Mass Flow Prediction

Figure 9 shows the cone meter discharge coefficient vs. Reynolds number relationship fitted by a linear equation. The discharge coefficient was fitted to a linear line at 0.3% uncertainty. As expected the pressure has no significant effect on the discharge coefficient. Figure 10 shows the calibration result of the vortex meter. A constant K-factor fitted the reference meter to 0.75%

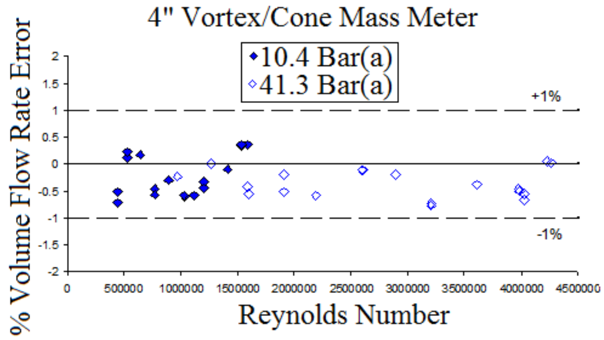

Fig 12. 4” Mass Meter Volume Flow Prediction

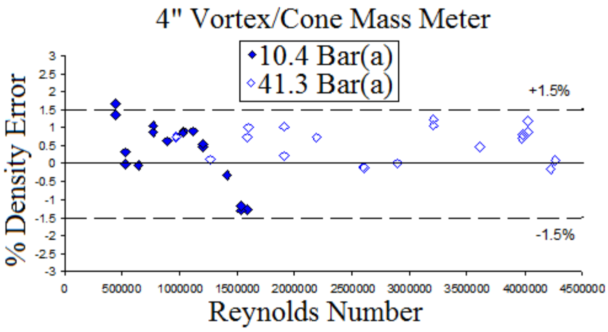

Fig 13. 4” Mass Meter Fluid Density Prediction

uncertainty. The calibrated meter predicted the volume flow (Figure 11), mass flow (Figure 12), and fluid density (Figure 13) to within 1%, 1%, and 1.5% at 95% confidence respectively.

5 A Field Example

Vortek Instruments and DP Diagnostics have built and tested at CEESI multiple such vortex / cone mass meters. Some examples are discussed by Sanford et al [5,10]. This meter design is now used in field applications. A field example is now discussed.

In some regions of the US oil is transported from local small well storage facilities by truck (e.g. see Figure 22). The storage facility meters the flow being loaded to the truck via volume change in the tank (for known oil density) while the truck has an independent check meter. For loss and accountability reasons this independent storage facility reference quantity of the trucks upload must match both the quantity stated by the truck metering system both loading and unloading to a low uncertainty. In this application oil can have a varying density between batches so it can be advantageous to use a mass meter.

The truck meter is mounted under the truck’s storage tank. Space is limited, and the installation naturally suffers from significant vibration as the truck is in motion, especially on unpaved surfaces. Traditionally a Coriolis meter was used. Coriolis meters are excellent mass meters, but for this specialist niche application, Coriolis meters have a relatively large footprint, are heavy, expensive and tend to have performance (zeroing) drift due to the excessive vibration inherent in

Fig 14. Two 4” Vortex / Cone Mass Meters Installed for Bi-Directional Flow Being Calibrated at CEESI.

Fig 15. Looking Downstream in a 4” Vortex / Cone Mass Meter.

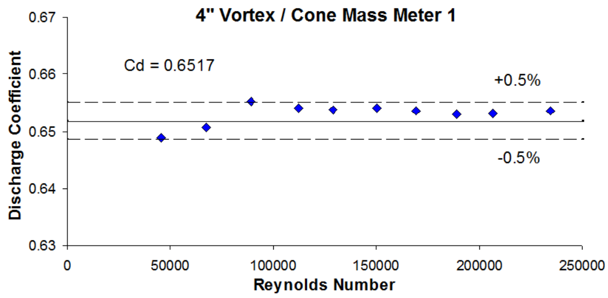

Fig 16. Meter 1 Cone Meter Calibration.

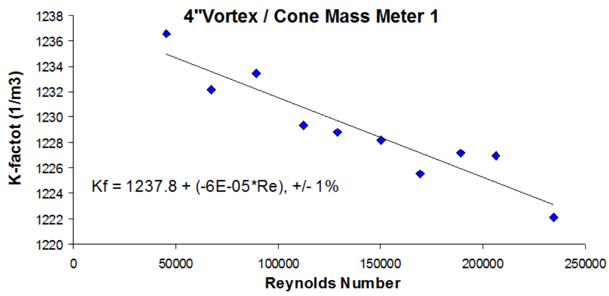

Fig 17. Meter 1 Vortex Meter Calibration.

the application. Therefore, this vortex / cone mass meter design was tested.

As the truck loads and unloads through a single pipeline and this meter design is unidirectional, two meters were installed close coupled for each direction. The two

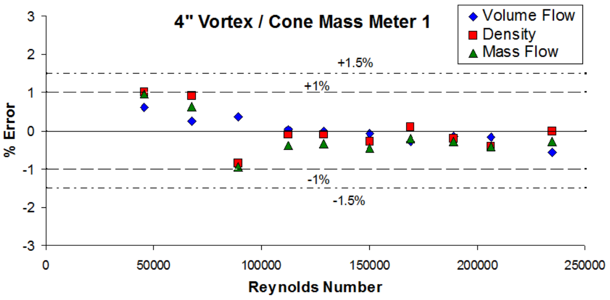

Fig 18. Meter 1 Mass, Volume, & Density Prediction from CEESI Calibration Data

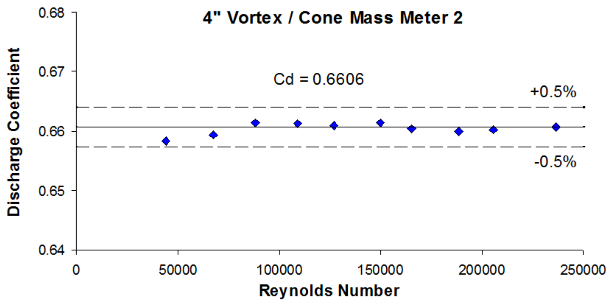

Fig 19. Meter 2 Cone Meter Calibration.

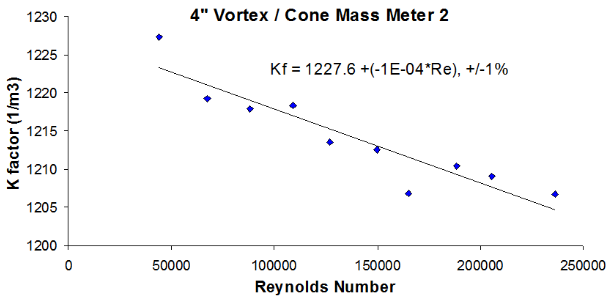

Fig 20. Meter 2 Vortex Meter Calibration

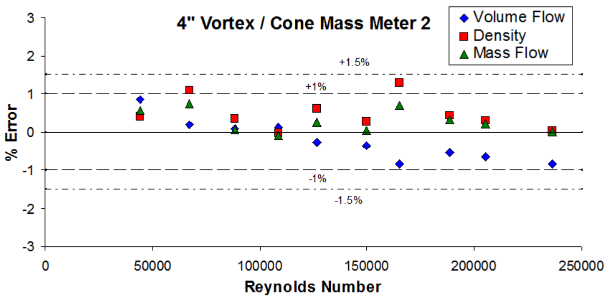

Fig 21. Meter 2 Mass, Volume, & Density Prediction from CEESI Calibration Data

meters were tested at the CEESI water flow facility in this configuration. Fig 14 shows these 4" meters installed at CEESI. Figure 15 shows a view looking downstream into one of these 4" vortex / cone mass meters. The vortex bluff body supports the cone element position one pipe diameter downstream.

Figures 16 & 17 show the stand alone cone and vortex meter sub-system CEESI calibration results respectively for the first 'loading' meter. Figures 19 & 20 show the stand alone cone and vortex meter sub-system CEESI calibration results respectively for the second

Fig 22. Truck with Vortex / Cone Mass Meters Installed

Fig 23. Front View of Meter Installations.

Fig 24. Back View of Meter Installations.

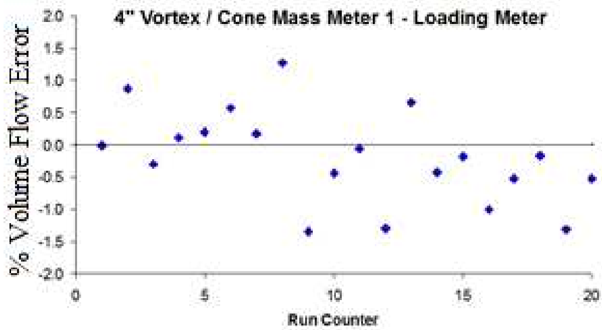

Fig 25. Load Meter Difference to Reference Values.

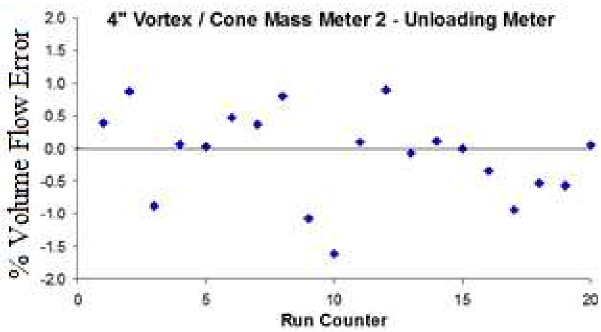

Fig 26. Unload Meter Difference to Reference Values.

'unloading' meter. These meters operate normally as if they are stand alone meters. Figures 18 & 21 show the CEESI calibration facility results for meters 1 & 2 respectively when their respective vortex & cone meter outputs are cross referenced. Both meters predicted the volume and mass flow rates to < 1% uncertainty and the density to < 1.5% uncertainty (at 95% confidence).

	Reference Meter 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.

These meters were installed under an oil truck (Figure 22), as shown in Figure 23 and 24. Figure 23 shows a front view with the vortex meter heads. Figure 24 shows the back view with the DP transmitters.

These meters have been used in multiple oil transfers. Figures 25 & 26 show sample loading (Meter 1) and unloading (Meter 2) field data. At the time of writing the field has only supplied the volume flow results, the authors are still waiting for the mass flow results. The data was recorded in batches (i.e. the run counter) that sum to the total batch quantity. There is a reasonable amount of scatter between run counts but the totalized value is what matters. Table 1 shows the reference quantity vs. the meters loading & unloading totalized values. The volume difference between this reference and the loading and unloading meters are -0.19% and -0.09% respectively. No zeroing / re-calibration was required in the field. The metering concept is proven to work.

6. The DP Meter Verification / Diagnostic System

A comprehensive DP meter verification / diagnostic system (or 'suite') can be included in this vortex / cone DP meter mass meter. An overview of these patented 'pressure field monitoring' diagnostics is now given. For details the reader should refer to the descriptions given in by Steven [6, 7], Skelton et al [8] & Rabone et al [9].

Figure 27 shows a sketch of the vortex / cone DP meter and its pressure field. (The vortex shedding sensor is not shown.) The DP meter has a third pressure tap downstream of the cone. This 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 12. The percentage difference between the inferred traditional DP (i.e. the sum of the recovered & PPL DPs) and the read traditional DP is $\delta\%$, while the maximum allowed difference is $\theta\%$.

Each DP can be used to independently meter the flow rate, as shown in equations 11, 13 & 14. Here $\dot{m}_{trad}$, $\dot{m}_{\exp}$ & $\dot{m}_{PPL}$ are the mass flow rate predictions of the traditional, expansion & PPL flow rate calculations with $x\%$, $y\%$ & $z\%$ uncertainties respectively. A is the inlet area and Kr & Kppl are the expansion & PPL coefficients respectively. Comparing these flow rate predictions produces three diagnostic checks. The percentage difference of the PPL to traditional flow rate calculations is denoted as $\psi\%$. The allowable difference is the root sum square of the PPL &

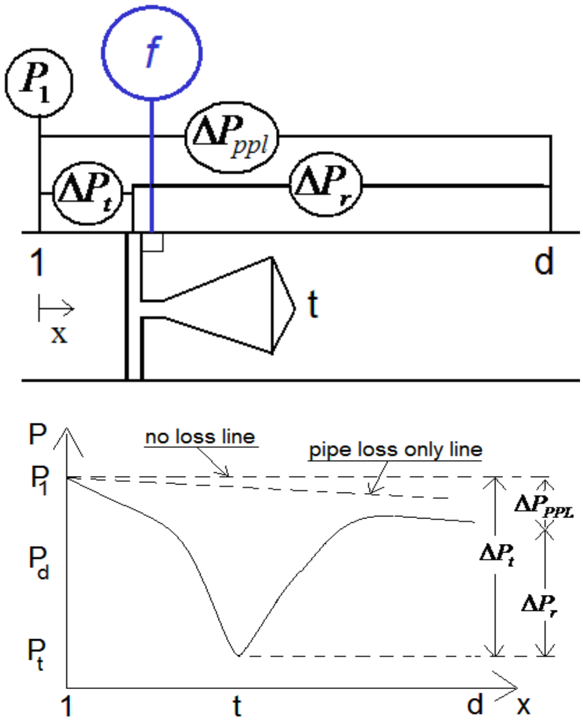

Fig 27. Cone meter with instrumentation sketch and pressure field graph.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \pm\ \theta\% \qquad \text{--- (12)}$$

Traditional flow calculation:

$$\dot{m}_t = EA_t\varepsilon C_d \sqrt{2\rho\Delta P_t} \quad \pm\ x\% \qquad \text{--- (11)}$$

Expansion flow calculation:

$$\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r} \quad \pm\ y\% \qquad \text{--- (13)}$$

PPL flow calculation:

$$\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}} \quad \pm\ z\% \qquad \text{--- (14)}$$

traditional meter uncertainties, $\phi\%$. The percentage difference of the expansion to traditional flow rate calculations is denoted as $\lambda\%$. The allowable difference is the root sum square of the expansion & traditional meter uncertainties, $\xi\%$. The percentage difference of the expansion to PPL flow rate calculations is denoted as $\chi\%$. The allowable difference is the root sum square of the expansion & PPL meter uncertainties, $\nu\%$.

Reading these three DPs produces three DP ratios, the 'PLR' (i.e. the PPL to traditional DP ratio), the PRR (i.e. the recovered to traditional DP ratio), the RPR (i.e. the recovered to PPL DP ratio). DP meters have predictable DP ratios. Therefore, comparison of each read to expected DP ratio produces three diagnostic checks. The percentage difference of the read to expected PLR is denoted as $\alpha\%$. The allowable difference is the expected PLR uncertainty, *a%*. The percentage difference of the read to expected PRR is denoted as $\gamma\%$. The allowable difference is the expected RPR uncertainty, *b%*. The percentage difference of the read to expected RPR is denoted as $\eta\%$. The allowable difference is the expected RPR uncertainty, *c%*.

These seven diagnostic results can be shown on the operator interface as plots on a graph. That is, we can plot (Figure 28) the following four co-ordinates to represent the seven diagnostic checks:

$$(\psi\%/\phi\%, \alpha\%/a\%), (\lambda\%/\xi\%, \gamma\%/b\%),$$
$$(\chi\%/\nu\%, \eta\%/c\%) \ \& \ (\delta\%/\theta\%, 0).$$

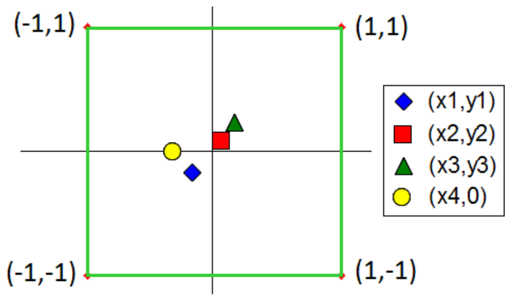

Fig 28. Normalized Diagnostic Box (NDB) with diagnostic results

For simplicity we can refer to these points as (x_1,y_1), (x_2,y_2), (x_3,y_3) & $(x_4,0)$. The act of dividing the seven raw diagnostic outputs by their respective uncertainties is called 'normalisation'. A Normalised Diagnostics Box (or 'NDB') of corner coordinates (1,1), (1,-1), (-1,-1) & (-1,1) can be plotted on the same graph (see Figure 6). This is the standard user interface with the diagnostic system 'Prognosis'. All four diagnostic points inside the NDB indicate a serviceable cone DP meter. One or more points outside the NDB indicate a meter system malfunction.

Examples of this verification / diagnostic system in operation with the vortex / cone DP meter mass meter is outwith the scope of this paper, but can be found in a paper by Sanford [10].

7. Conclusions

There are advantages to directly metering flow by mass. This approach can either eliminate the requirement for an independent density measurement or act as a check against the independent density measurement. Presently only Coriolis meter technology is available as a non-niche general mass meter. Whereas Coriolis meters are proven to be excellent mass meters with low metering uncertainty they do suffer from disadvantages such as being large by volume & weight, high permanent pressure loss and being relatively expensive. There is therefore still a niche market for a simple, relatively inexpensive mass flow meter.

Vortek Instruments & DP Diagnostics have overcome the practical problems early developers found when applying the simple Boden mass flow meter concept to produce a viable simple mass meter. Multiple laboratory and field tests have shown this hybrid vortex / cone DP meter design is a viable practical industrial gas or liquid mass meter design. One such field test showed that this mass meter could meter an oil flow to very low uncertainty.

The cone DP meter sub-system can also have the latest DP meter verification / diagnostic system.

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