GAS MASS FLOW METERING
AN ALTERNATIVE APPROACH

Eric Sanford, Vortek Instruments
Koichi Igarashi, Azbil North America
Kim Lewis, DP Diagnostics

1 INTRODUCTION

Metering a fluid's mass flow rate in a pipe with methods that do not require an external fluid density prediction is an attractive option in many flow meter applications. 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.

Gas flow must ultimately be metered by mass flow. A steady gas flow throughout a pipeline has a constant gas mass flow rate but a varying volume flow rate. A gas mass flow rate reading is an absolute statement of the gas quantity flowing in the system. However, a gas volume flow rate reading is only true at the meter location. Flow meters that read a volume flow rate prediction require an independent gas density prediction at the meter location in order to give the required mass flow rate. The Achilles heel of most gas meter designs is that they are wholly dependent on the independent gas density prediction being available (and trustworthy). Therefore, for some meter applications it can be preferable to meter mass flow using physical principles that that do not require the independent measurement of fluid density.

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. It is widely assumed that there is no viable alternative, i.e. no competing general purpose mass flow meter technology. However, an alternative gas mass flow meter design has been known for at least 50 years. In 1956 Boden [1] patented the concept of cross referencing the outputs of a density sensitive and density insensitive flow meters. This combination 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 computers were available to make such a system practically and economically viable,
- Two meters in series can be perceived as a heavy & expensive "contraption" meaning that a practical design needs to be a compact hybrid design,
- There is a practical design complication that becomes evident when developing a compact hybrid design.

In this paper the Boden concept is described along with the practical design problem when developing such a mass meter. A new hybrid design consisting of a DP meter & a vortex meter will be introduced that has been developed to circumvent this design problem. Data from test meters and the first commercial meter will be shown. The DP meter is fully equipped with the modern DP meter diagnostic system 'Prognosis'.

2 THE HISTORY OF THE BODEN MASS METER CONCEPT

In 1956 Boden [1], working in the aeronautical industry, 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).

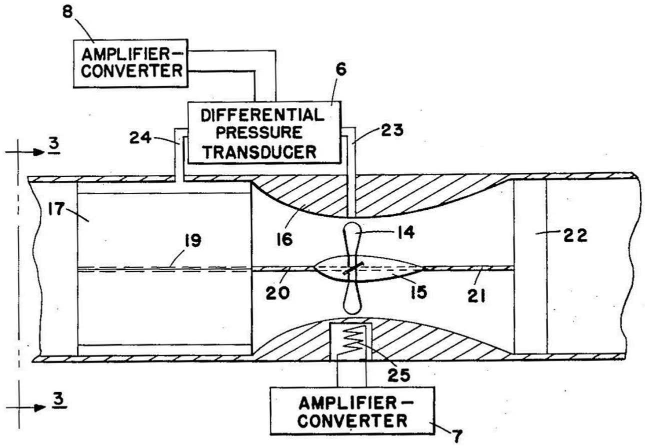

Fig 1. Boden et al, Turbine + Venturi Meter Combination 1956

In 1967 Pfrehm [2], an Esso engineer, modified & improved this design. Considering the adverse effects of a turbine meter in a Venturi meter throat too excessive on the Venturi meter performance Pfrehm suggested that the DP meter would operate better if the low pressure port was located away from the turbine meter. Pfrehm, suggested a heavily modified Venturi tube. The Pfrehm design is shown in Figure 2. However, the Pfrehm design still produces a highly unorthodox Venturi meter with questionable performance.

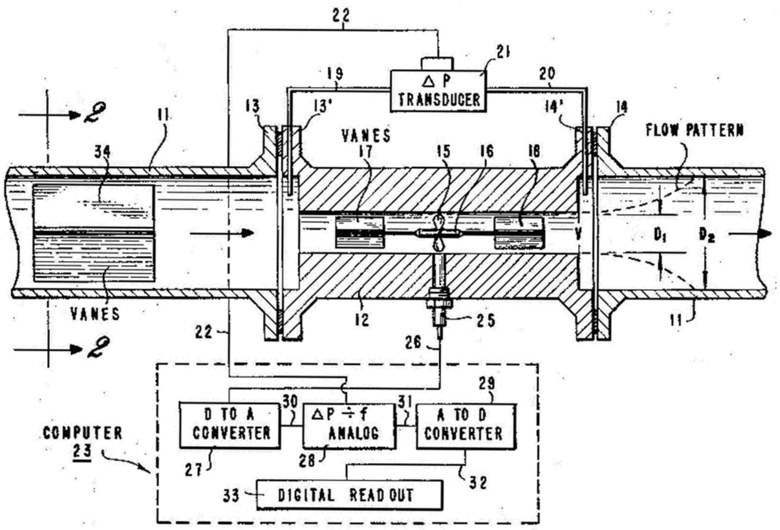

Fig 2. Pfrehm, Turbine + Modified Venturi Meter Combination 1967

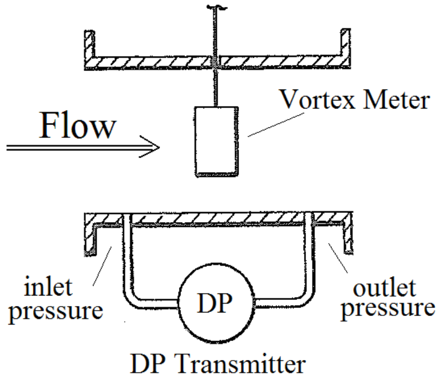

Fig 3. Lisi's Mass Meter Arrangement

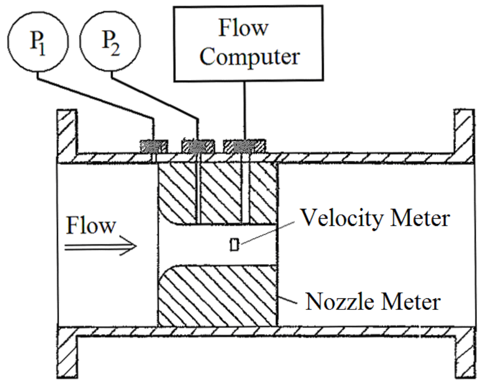

Fig 4. Mottram's Mass Meter Arrangement

In 1974 Lisi [3], another Esso engineer, considered a different combination of density sensitive & density insensitive flow meters. Lisi suggested that as a vortex meter has no moving parts it may be a better choice than a turbine meter to put in series with a DP meter. Lisi considered 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).

In the early 1970's Klaus Zanker of Kent Industries in the UK also investigated this generic concept. At that time Kent Industries judged the concept not commercially viable due to these paired flow meters having distinctly different performances. This R&D project would also have been hindered by early flow computer capabilities and the then lesser commercial demand for gas mass metering.

In 1986 Mottram [4] patented another density insensitive and density sensitive flow meter combination. Mottram 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. Mottram's list of prior art did not mention any of these earlier developments.

By 2005 no such device had been marketed. Knowledge of this concept was not even known to many who would have reasonably considered themselves 'skilled in the art' of flow meter design. As such, in 2005 Dimarco S. et al [5] of Rosemount Inc (owned by Emerson Process) submitted a patent application on this very same generic idea. Rosemount did not state Boden [1], Pfrehm [2], Lisi [3] or Mottram [4] as prior art. Like Mottram, Rosemount Inc / Emerson Process were unaware that there were reinventing a concept that had been reinvented and modified several times over several decades.

In 2006 Steven [6], while being just as uninformed as Mottram & Dimarco et al also submitted a patent on this generic idea. This patent application listed various different potential designs where various meters were combined to produce hybrid mass meter designs. These suggested designs inadvertently including the prior art of Pfrehm & Lisi designs. However, other designs were also suggested. These included placing an ultrasonic volume flow meter in the throat of a Venturi or nozzle meter, or combining vortex & cone DP meters by replacing the cone element support with a vortex meter bluff body.

If knowledge of the prior art had been more widespread, then Mottram [4], Dimarco [5], & Steven [6] would have known the generic concept was prior art, the various patents had expired and the generic methodology was now obscure but free public knowledge. However, there are obvious under lying questions. There is an industrial requirement for mass flow metering, and this concept has been continually reinvented as a good idea. So why has this concept repeatedly failed to be developed into a product? Why is this concept not better known amongst flow meter engineers who were skilled in the art?

One issue is that when Boden, Pfrehm & Lisi were researching the concept the computer power was not easily available to cross reference the two meter outputs. It was a good theoretical idea but difficult to implement in practice. Once, the computer power was readily available as of the 1980's practical problems appeared when attempting to develop a commercial product.

The primary idea by Boden [1] is to put separate meters in series. This was also discussed by Lisi [3], Damarco [5] & Steven [6]. Few operators wish to purchase two separate flow meters for a single flow metering application. It is more expense, more maintenance, more footprint etc. A single hybrid meter is far more attractive. However, whereas combining density sensitive & density insensitive flow meters to produce a single hybrid meter design is theoretically sound, in practice it can suffer from some practical limitations. The devil is in the detail. The Boden [1], Pfrehm [2], Lisi [3], Mottram [4] & some of Steven's [6] hybrid designs suffer from the same practical flaw. The two meters are equally important for the concept to operate successfully. However, these designs tend to inherently chose one meter as the primary meter. The other meter's performance is compromised by attempts to fit it into the other primary or 'main' meter. For example:

- Boden [1]: The primary meter is the turbine (density insensitive) meter. It is positioned in the Venturi meter throat where flow velocity is highest and the turbine meter works best. The turbine meter will disturb the flow in the Venturi meter throat. The turbine meter size limits the choice of the Venturi meter throat. That is, the Venturi meter cannot be independently sized to the most appropriate beta (throat to inlet diameter ratio) value for any particular application. Without free range to fit an appropriate DP meter beta value, it is not possible to set the Venturi meter flow range as the same as the turbine meter. The Venturi meter performance is compromised.

- Pfrehm [2]: The primary meter is the turbine (density insensitive) meter. It is still positioned in the throat of the Venturi meter. Pfrehm did state that the Boden [1] design compromised the Venturi meter performance. The Pfrehm design attempted to somewhat improve the Venturi meter performance. However, the improvement was marginal. The Venturi meter still can not be independently sized to its best beta value. The Venturi meter performance is still compromised.

- Lisi [3]: The primary meter is the vortex (density insensitive) meter. The 'DP meter' is the vortex meter bluff body with a DP read across it. A vortex meter bluff body makes a poor DP meter primary element. It produces low DPs at even moderate to high flow rates meaning a limited useable flow range, and a range that is mis-matched with the vortex meter range. In this hybrid design the DP meter is compromised.

- Mottram [4]: The primary meter is the vortex (density insensitive) meter. It is positioned in the throat of the nozzle meter. The nozzle meter may be affected by the presence of the vortex meter in its throat and the throat cannot be sized independently of the vortex meter. In this hybrid design the nozzle meter performance is compromised.

- Steven [6], Venturi / Nozzle with ultrasonic meter design. When placing an ultrasonic meter in the throat of a Venturi meter both meters can be compromised. The minimum practical size of ultrasonic meters limits the choice of the Venturi meter throat. That is, the Venturi meter cannot be independently sized to the most appropriate beta value for any particular application. Therefore, the Venturi meter performance is compromised. Furthermore, the local gas velocity in a mid-beta Venturi meter throat is much greater than in the pipe line. For example a 0.5 beta Venturi meter with a 20 m/s inlet velocity has an 80 m/s throat velocity. Such high velocities compromise the ultrasonic meter due to excessive noise. Also, ultrasonic meters do not operate at peak performance in very low pressure gas applications.

Modern day computers are of course easily capable of cross referencing these meters outputs. If a hybrid design can be produced such that the meters operate together across the same flow range both to reasonable accuracy then the concept should 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. DP Diagnostics has now developed such a meter with Vortek Instruments. This consists of a vortex (density insensitive) meter in combination with a cone DP (density sensitive) meter.

In order to describe how this meter operates it is first necessary to review vortex meter and DP meter operating principles.

3 VORTEX SHEDDING FLOW METER THEORY

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" after the aerodynamicist Theodore von Karman. 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.

Vincenc Strouhal studied the phenomenon of vortex shedding. The Strouhal number, defined by equation 1, is a constant over a large turn down (at least for non-insertion vortex meters). For even larger turn downs the Strouhal number may be sensitive to velocity (or Reynolds number). When the Strouhal number (St) is found by flow

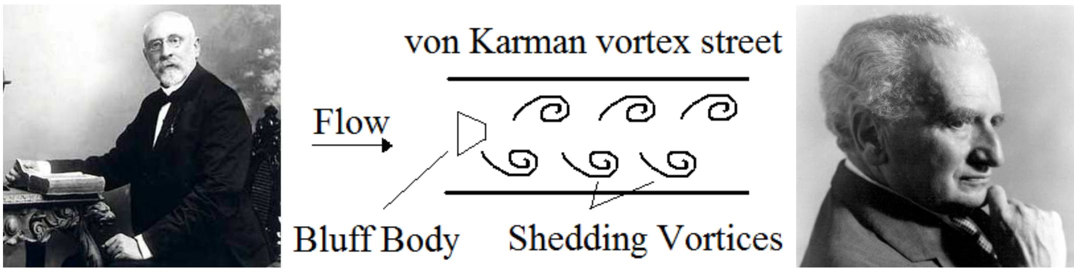

Fig. 5 Vincenc Strouhal (left), Theodore von Karman (right), and the principle of cyclic vortex shedding from a bluff body.

calibration, then the average velocity (U_1) can be found by reading the vortex shedding frequency (f), and knowing the bluff body width (d), (see equations 1a & 2).

$$St = \frac{fd}{U_1} \text{ ---- (1)} \qquad U_1 = \frac{fd}{St} = \frac{f}{C} \text{ ---- (1a)} \quad \text{where} \quad C = \frac{St}{d} \text{ ---- (2)}$$

The volume flow rate, $\dot{Q}$ is therefore calculated by:

$$\dot{Q} = A_1 U_1 = A_1 \frac{f}{C} = \frac{f}{K_v} \text{ ---- (3)} \quad \text{where} \quad K_v = \frac{C}{A_1} = \frac{St}{Ad} \text{ ---- (4)}$$

where "A_1" is the cross sectional area of the meter inlet and "K_v" is the vortex meter "K-factor" which is usually found by calibration. Therefore, the generic vortex meter volume flow rate equation is equation 3. 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.

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 5), means that an iteration on the average velocity is required to solve for volume flow rate, i.e. Equation 6 requires an iterative solution.

$$K_v = f_1(U_1) \qquad \text{--- (5)}$$

$$\dot{Q} = A_1 U_1 = \frac{f}{K_v} = \frac{f}{f_1(U_1)} \qquad \text{--- (6)}$$

The mass flow rate is found from Equation 7.

$$m = \rho Q \qquad \text{--- (7)}$$

Therefore, in order to predict the mass flow rate, the stand-alone vortex meter requires the fluid density from an external source, e.g. use of a densitometer or a pressure, volume and temperature (or "PVT") equation of state calculation based on a known fluid properties and pressure & temperature readings.

For a more in-depth discussion on vortex shedding flow meter technologies see Storer [7].

4 DIFFERENTIAL PRESSURE (DP) FLOW METER THEORY

The first widely publicized DP meter was the Venturi meter developed by Clemens Herschel in 1885 based on the work of Giovanni Venturi in 1797. Giovanni Venturi combined the laws of conservation of mass (as discovered by Lavoisier) and conservation of energy in fluid flows (as described by Bernoulli) to produce the DP meter concept. Since Herschel's first 'Venturi' 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.

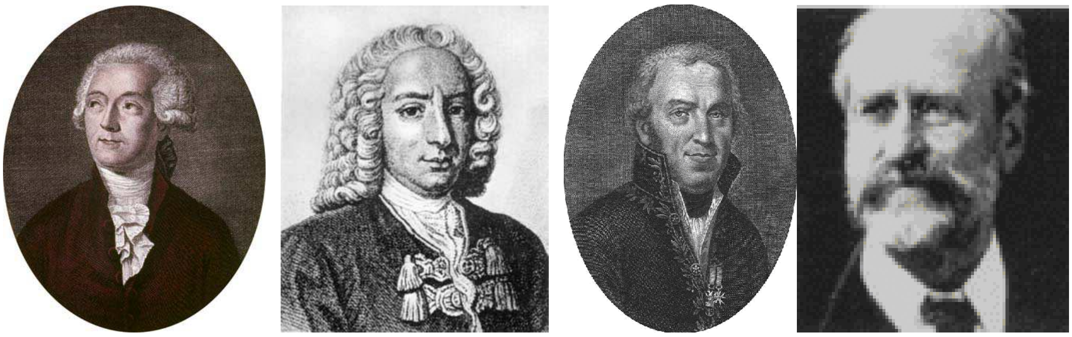

Fig 6. Left to Right, Antoine Lavoisier, Daniel Bernoulli, Giovanni Battista Venturi, & Clemens Herschel.

There is a common misconception in the modern industry (often promoted by the marketing of competing flow meter technologies) that DP meters are an aging technology. It is all too often claimed, in a rather derogatorily tone, that the DP meter is "just the application of Benoulli's principle". However, such claims are disingenuous. Flow meters are not fashion accessories, they are an industrial requirement, and their aim is to meter the flow as simply, reliability and inexpensively as possible. Therefore, if this can be achieved by "just applying the Bernoulli principle", then why not ***just*** apply the Bernoulli principle!? However, the common belief that DP meters operate by just applying the Benoulli principle is technically wrong. Bernoulli's principle alone cannot be used to find a fluids flow rate. The Bernoulli principle (i.e. the conservation of the flows energy) must be cross referenced with Lavoisier's principle of the conservation of mass for the flow rate to be found. This is how a DP meter actually operates. Neither of the physical laws of the conservation of mass or energy alone can be used in isolation to find the flow rate. It is the concept of combining these laws that creates the DP meter. Therefore, DP meters operate by cross-referencing two of the most fundamental laws of physics. This makes DP meters extremely simple, yet robust and reliable.

Figure 7 shows a sketch of a generic DP meter, with an inlet (subscript "1") and a minimum cross sectional area, or 'throat' (denoted by the subscript "t"). The inlet pressure P_1 is usually read (with the system temperature). This information is traditionally combined with independent knowledge of the gas composition to allow a 'PVT' equation of state calculation of gas density. The differential pressure (DP_t) is directly read. The conservation of mass flow (m) between the inlet cross sectional area (A_1) and the throat cross sectional area (A_t) for an incompressible flow is expressed by Equation 7a. Note that ρ denotes the fluid density, Q denotes the volume flow rate, and U_1 & U_t denote the average fluid velocity at the inlet and throat sections respectively.

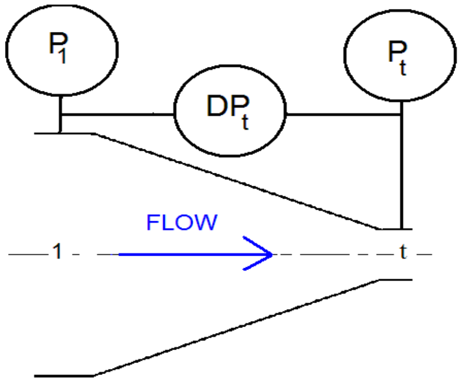

Fig 7. Sketch of Generic DP Flow Meter

Conservation of mass expression: $m = \rho Q = \rho A_1 U_1 = \rho A_t U_t$ --- (7a)

Re-arranging the conservation of mass expression: $U_1 = \frac{A_t}{A_1} U_t$ --- (8)

For incompressible flow the density is constant and hence Equation 7a can be expressed as Equation 8. The conservation of mass flow dictates that the DP meter geometry (i.e. the throat to inlet area ratio) sets the throat to inlet fluid velocity ratio. On its own, this is all the law of conservation of mass can tell us. It is not possible to find the flow rate through the DP meter using the law of conservation of mass alone.

Conservation of energy expression: $\frac{P_1}{\rho} + \frac{U_1^2}{2} = \frac{P_t}{\rho} + \frac{U_t^2}{2}$ --- (9)

Re-arranging the conservation of energy expression: $U_1 = \sqrt{U_t^2 - \frac{2\Delta P}{\rho}}$ --- (10)

A horizontal incompressible no loss flows conservation of the energy between the inlet cross sectional area (A_1) and the throat cross sectional area (A_t) is expressed by Equation 9. This is Bernoulli's theorem. For incompressible flow the density is constant and hence Equation 9 can be expressed as Equation 10. The conservation of energy dictates that the relationship between the average inlet and throat fluid velocities is dictated by the differential pressure and fluid density. On its own, this is all Bernoulli's theorem can tell us. That is, for any given inlet velocity, the throat velocity is dictated by the differential pressure and the fluid density. It is not possible to find the flow rate through the DP meter using the law of conservation of energy, i.e. the "Bernoulli theorem", alone.

The relationship between the inlet and throat velocities *must* satisfy *both* the laws of conservation of mass and energy. Therefore, equating the throat velocity expression from the conservation of mass & energy expressions gives Equation 11. Re-arranging gives Equation 12. Substituting equation 12 into equation 7 produces the mass flow expression equation 13. Note that beta (β), a geometry value for a given DP meter, is defined by equation 14. The "Velocity of Approach" (denoted as 'E') is defined as equation 15.

$$U_1 = \frac{A_t}{A_1} U_t = \sqrt{U_t^2 - \frac{2\Delta P}{\rho}} \quad \text{--- (11)} \qquad U_t = \sqrt{\frac{2\Delta P}{\rho\left\{1 - \left(\frac{A_1}{A_t}\right)^2\right\}}} \quad \text{--- (12)}$$

$$m = \rho Q = \rho A_t U_t = \rho A_t \sqrt{\frac{2\Delta P}{\rho\left\{1 - \left(\frac{A_1}{A_t}\right)^2\right\}}} = E A_t \sqrt{2\rho \Delta P_t} \quad \text{--- (13)}$$

$$\beta = \sqrt{\frac{A_t}{A_1}} \quad \text{--- (14)} \qquad E = \frac{1}{\sqrt{1-\beta^4}} \quad \text{--- (15)}$$

Equation 13 is the DP meter idealized mass flow rate equation. The actual gas DP meter's flow rate equation also includes an expansion term denoted by "ε" to account for density changes through the meter, and a discharge coefficient denoted by "C_d" to account for other differences between the ideal and actual operation of the meter. The actual generic DP meter mass flow rate equation is shown as equation 16. It follows that the DP meter expression for actual volume flow rate is equation 16a. Note, that to predict the mass or volume flow rate with a DP meter requires the density be known from an external source. As with the vortex meter this is usually via a densitometer or a "PVT" equation of state calculation.

$$m = \rho Q = E A_t \varepsilon C_d \sqrt{2\rho \Delta P_t} \quad \text{--- (16)}$$

$$Q = E A_t \varepsilon C_d \sqrt{\frac{2\Delta P_t}{\rho}} \quad \text{--- (16a)}$$

5 BODEN MASS FLOW METERING

Let us consider a vortex meter and a DP meter in series. A vortex meter finds the volume flow rate by equation 6, where the vortex meter K-factor is usually considered to be a constant value. A DP meter (such as a cone meter) finds the volume flow rate by equation 16a. Equating the vortex meter and DP meter volume flow rate equations (i.e. Equations 6 & 16a) gives Equation 17. Re-arranging this expression produces an expression for the fluid density, i.e. Equation 18.

$$Q = \frac{f}{K_v} = E A_t \varepsilon C_d \sqrt{\frac{2\Delta P_t}{\rho}} \quad \text{--- (17)}$$

$$\rho = (2\Delta P)\left(\frac{K_v E A_t \varepsilon C_d}{f}\right)^2 \quad \text{--- (18)}$$

The expansion factor is a function of the inlet pressure, the differential pressure, the DP meter's beta and the isentropic exponent (see Equation 19). The beta value is a known constant geometric value, and the inlet pressure and differential pressure are measured.

The isentropic exponent is a gas property. However, for any given type of gas it is a known value that is effectively constant over a large thermodynamic range. Furthermore, the flow rate prediction sensitivity to isentropic expansion value uncertainty is extremely low. Uncertainty in a gases isentropic exponent is a third order issue.

$$\varepsilon = f\left(P, \Delta P_t, \beta, \kappa\right) \qquad \text{--- (19)}$$

Therefore consider Equations 18 & 19. The velocity of approach (*E*), beta value (*β*) & throat area (A_t) are known geometric constants. The inlet pressure (*P*), the DP (*ΔP*) & the vortex shedding frequency (*f*) are read. Therefore, with a known isentropic exponent, if the vortex meter K-factor and the DP meter discharge coefficient values are constants, the density of the fluid is directly found via Equation 18. Then, as the volume flow rate is known from the vortex meter Equation 6, the mass flow rate is found via Equation 7.

In cases where the lowest possible uncertainty is required, the vortex meter K-factor may be expressed as a function of gas velocity (see Equation 5). This function is formed by data fitting the calibration results. In such a case the volume flow rate is still predicted by the stand alone vortex meter, by iterating Equation 5 on the gas velocity, to give the volume flow rate prediction (Q_{vortex}). The DP meter discharge coefficient may need to be expressed as a function of the Reynolds number (see Equation 20). This function is formed by data fitting the calibration results.

$$C_d = f\left(\mathrm{Re}\right) \qquad \text{--- (20)}$$

Such a scenario is represented Equation 17a. The associated fluid density calculation is shown as equation 17b. However, this expression has two unknowns, i.e. the fluid density ***and*** Reynolds number. Equation 21 shows the Reynolds number calculation. Equation 21 is substituted into equation 17b. There are still two unknowns, i.e. the fluid density ***and*** viscosity (*μ*). It is necessary to supply the fluid viscosity to the fluid density calculation. This is the price of requiring reduced uncertainty.

$$Q_{vortex} = EA_t\varepsilon\left\{f\left(\mathrm{Re}\right)\right\}\sqrt{\frac{2\Delta P_t}{\rho}} \qquad \text{--- (17a)}$$

$$\rho = \left(2\Delta P\right)\left(\frac{EA_t\varepsilon\left\{f\left(\mathrm{Re}\right)\right\}}{Q_{vortex}}\right)^2 \qquad \text{--- (17b)}$$

$$\mathrm{Re} = \frac{4\rho\dot{Q}}{\pi\mu D} \qquad \text{--- (21)}$$

In summary, when using a constant DP meter discharge coefficient and an approximate isentropic exponent value this methodology can produce a fluid density prediction, and a volume and mass flow rate prediction. For optimized performance (i.e. minimum output uncertainty) the discharge coefficient can be fitted to the Reynolds number, meaning that the operator has to supply the fluid viscosity. For gas flows this is often not a serious hindrance. Gas viscosities are reasonably well known at a given temperature, and the calculation has a low sensitivity to viscosity uncertainty.

5a INITIAL DP DIAGNOSTICS AND VORTEK INSTRUMENTS RESEARCH

The initial DP Diagnostics and VorTek Instruments research tested Lisis's idea of using a stand alone vortex meter and reading the DP across the bluff body as a 'DP meter'. The problems found by Kent Industries in the 1970's were confirmed. Across the vortex meter's flow range the DPs produced were low. There was a mis-match in this designs 'DP meter' & vortex meter practical flow ranges. As the concept requires both meters operate well across the same flow range this 'DP meter' design is not a practical replacement of a stand alone DP meter.

This is the Achilles heel of all previous hybrid designs. The DP meter has been compromised by the requirements of the accompanying density insensitive meter limiting the choice of the DP meter's beta (and hence practical flow range). Furthermore, the DP meters chosen in these existing designs were all to an extent compromised by the flow disturbance caused by the presence of the density insensitive meter.

The vortex / cone DP meter combination offered a solution to these problems. The cone meter is so resistant to upstream disturbances that it should not be significantly adversely affected by the presence of a vortex meter close coupled upstream. A series of tests of separate vortex and cone DP meters in series were conducted. These 4" meter tests confirmed that both the vortex & cone DP meters continued to operate normally down to the minimum spacing tested, i.e. the vortex meter two pipe diameters (2D) upstream of the apex (i.e. nose section) of the cone. (A detailed discussion on this early research project is given by Storer et al [8].)

Fig 8. First 4" Prototype Mass & Volume Flow Meter and Densitometer

A 4" spool containing a vortex meter 3D upstream of the cone meter was produced, as shown in Figure 8. Figure 8 shows the vortex meter systems flow computer casing connected above the vortex shedding bluff body at the inlet to the 4", schedule 80, meter body. Close to the mid-point of the meter body there are two pressure tappings. These are the standard cone DP meter inlet and low pressure cone pressure taps. Figure 9 shows a downstream view. The cone meter had a 0.75β. This beta was chosen to show that even a relatively small cone was resistant to upstream disturbance caused by the vortex meter. Figure 8 also shows a wall pressure tapping downstream of the cone. This is to allow the cone DP meter to incorporate the generic DP meter diagnostic system 'Prognosis'. With this extra length to accommodate the downstream pressure tapping this 4" meter was 11D long at 42 inches (3.5 ft) long. If DP meter diagnostics were not required this 4" mass flow meter would have been approximately 8D at 31 inches (2 ½ ft) long.

The CEESI air tests had a turndown of 14:1 (i.e. $6.4e6 \leq Re \leq 4.3e5$). Three nominal pressures were set at 14 Bar (16 kg/m^3), 27 Bar (32 kg/m^3) & 41 Bar (48 kg/m^3). The subsequent calibration of the independent meters are shown in Figures 9 & 10. The cone DP meter expansibility calculation was taken from Stewart [9]. Figure 9 shows the vortex meter K-factor set to a constant value with an uncertainty of ±0.5%. Figure 10 shows the DP meter discharge coefficient fit. A constant discharge coefficient fitted the data to an uncertainty of ±0.5%. A linear fit to Reynolds number fitted the data to ±0.35%.

With a constant K-factor the vortex meter predicted the volume flow rate directly (see Figure 11). The mass flow rate and density were predicted by combining this volume meter output with the cone DP meter with the liner discharge coefficient fit. The results are shown in Figures 12 & 13 respectively. The volume flow rate prediction had < 0.5% uncertainty. The mass flow rate prediction had < 0.5% uncertainty. The gas density prediction had < 1% uncertainty.

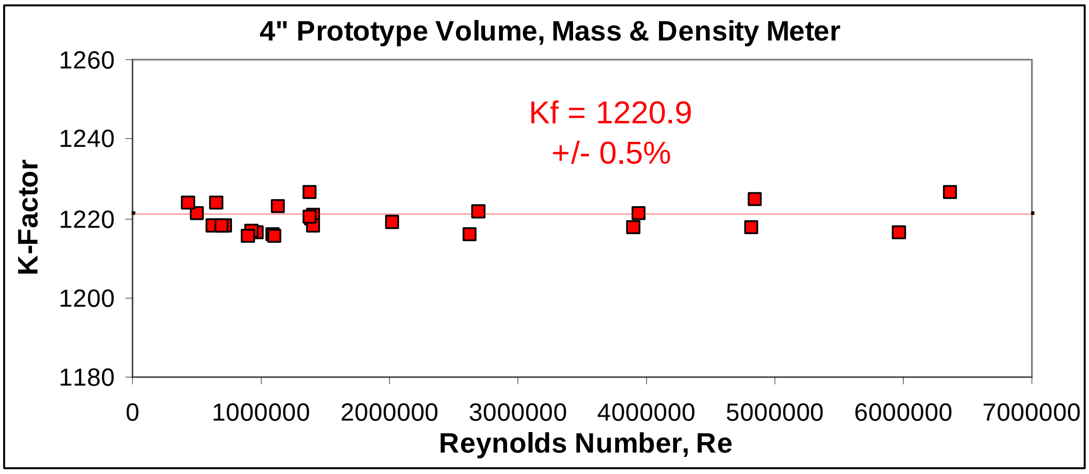

Fig. 9. 4" Prototype Meters Vortex K-Factor, Fitted as a Constant Value.

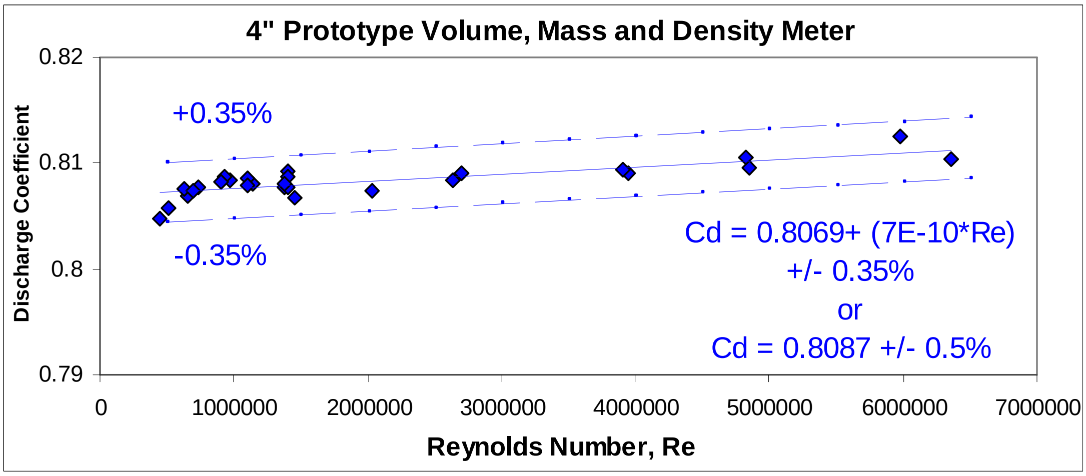

Fig. 10. 4" Prototype meter DP Discharge Coefficient, as a Function of Reynolds No.

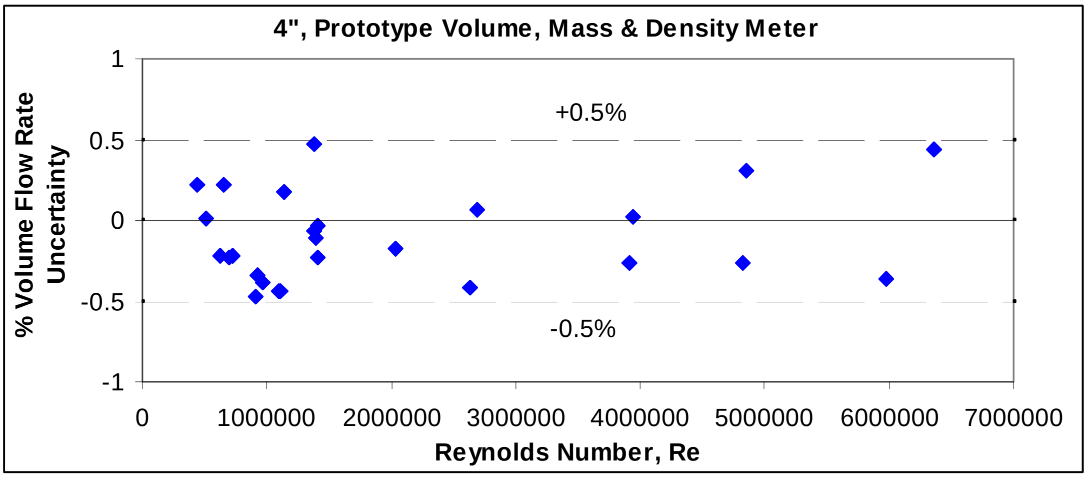

Fig 11. 4" Prototype Meter Volume Flow Rate Prediction.

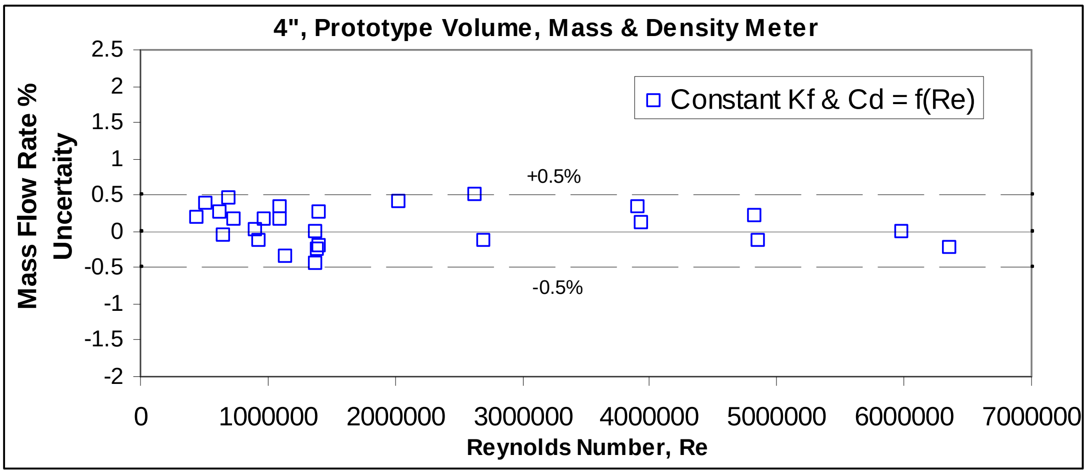

Fig 12. 4" Prototype Meters Mass Flow Rate Prediction.

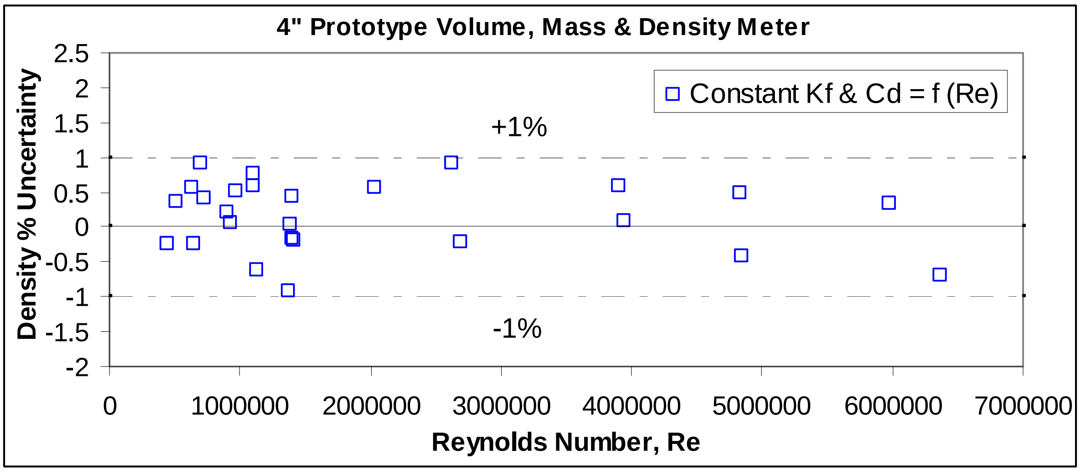

Fig 13. 4" Prototype Meter Density Prediction.

Note that the system is required to know the gas flow's isentropic exponent and the gas viscosity. 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.

5b DESIGNIING A HYBRID VORTEX / CONE DP METER

Having confirmed that a vortex meter in close proximity to a downstream cone DP meter was a viable mass meter system it was now necessary to produce a hybrid system in order to make the system more compact, lighter and attractive to industry. This task proved to be more difficult than first envisaged. It took four design iterations to achieve this goal. The devil was in the detail.

5b.1 How Not To Design a Hybrid Vortex / Cone DP Meter

The standard cone DP meter has a cone support that extends vertically down from the wall to the centre line, where it is attached to the apex of the cone. The initial hybrid design replaced this circular cone support with a vortex meter bluff body. This bluff body / cone support bar extended down to the centre line only. The vortex shedding sensing device was positioned at the standard position downstream of the bluff body. The cone element was positioned at its normal location downstream of its support bar. This design is drawn in Figure 14.

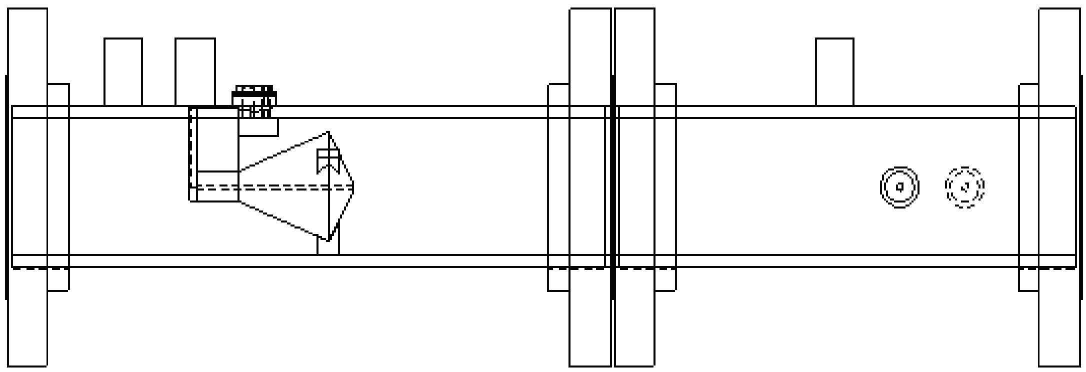

Fig. 14. Initial Hybrid Vortex / Cone DP Meter Design

Air flow testing this design at CEESI showed that whereas the cone meter operated normally the vortex meter was unserviceable with no vortex shedding read. Vortek Instruments postulated that the problem was that the bluff body did not extend across the entire diameter of the meter body. Insertion vortex meters, like integral vortex meters, usually have bluff bodies that extend the across the full pipe diameter. Shorter bluff body lengths have been known to have vortex shedding problems. This hybrid design was not viable.

The second hybrid design extended the bluff body / cone support to the full meter body diameter. This second iteration design is drawn in Figure 15. This design now had a standard vortex meter bluff body design. As the bluff body was the length of the meter body diameter it was attached at both ends to the wall. This design gave the bluff body more chance of producing the required vortex shedding while it significantly increased the stiffness of the bluff body / cone assembly. This reduces the likelihood of any long term fatigue failure, while also increasing the overall strength of the assembly.

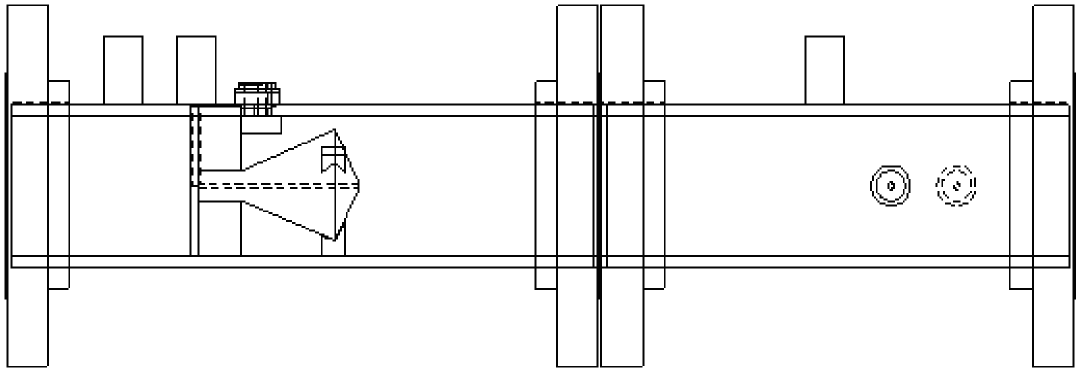

Fig. 15. Second Hybrid Vortex / Cone DP Meter Design

Air flow testing this design at CEESI showed that again the cone meter operated correctly but the vortex meter was still unserviceable. The vortex shedding was intermittent and not reliable. Vortek Instruments postulated that the problem was that the proximity of the vortex shedding sensor to the downstream cone element. The vortex shedding sensor overlapped the nose of the cone. As the reducing cross sectional area / flow acceleration is a known flow disturbance mitigater, it was suspected that the cone was dissipating the von Karman vortex street. This hybrid design was therefore not viable. The cone meter had to be withdrawn further downstream to allow the vortex shedding sensor to be upstream of the cone element. With successful earlier tests of a stand-alone vortex meter 2D upstream of a cone meter it was realized that the distance did not have to be excessive.

For the third design iteration the question became how far downstream must the cone element be from the vortex meter sensor in order for the vortex meter to be unaffected by the presence of the cone element? It was decided to build a test meter with a replaceable cone element such that the distance between the vortex meter bluff body and the apex of the cone was variable. The bluff body and cone element were connected by a hollow circular bar. This ran along the meter body centre line and screwed into the bluff body and cone element. The distance between the bluff body and cone element could be varied by changing the bar length between tests. This would avoid the necessity to build different test meters with different bluff body / cone element distances.

Such a replaceable cone meter design was used in the early 2000's by McCrometer for R&D purposes, Cameron considered such a design in the mid 2000's, and Dynamic Flow purports to have 'invented' this concept more recently. However, this particular design was singularly used here for R&D convenience, it was not considered as part of any commercial finished design. This third iteration design is drawn in Figure 16.

Air flow testing this design at CEESI, with a 1.5D spacing between the bluff body and cone apex, showed that this time the vortex meter operated correctly but that the cone meter had highly variable and untrustworthy DP readings. Subsequent inspection found galled threads on the connecting bar. This was a lesson on the practical problems of replaceable cone element designs. Replaceable cone elements usually means a thread is required to connect the cone element to the meter. This is a weak point on the design. It is essential for the successful operation of a cone meter that there is no leak in the conduit

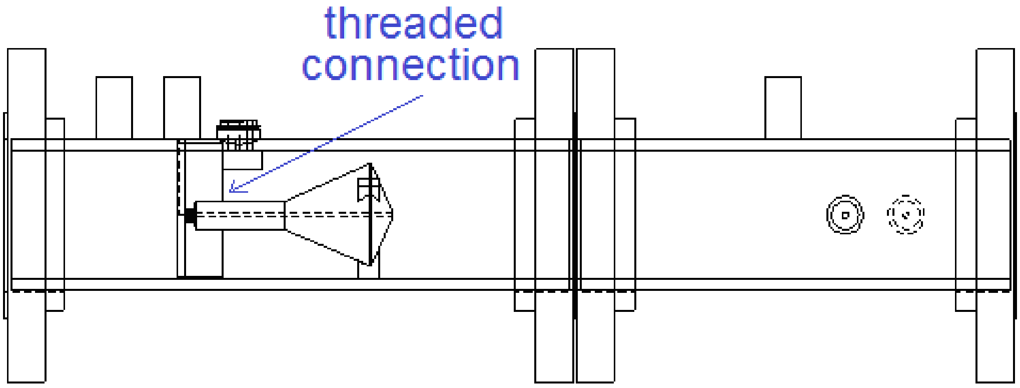

Fig. 16. Third Hybrid Vortex / Cone DP Meter Design

running from the back face of the cone through the cone and up the support bar to the low pressure port. The galled thread was leaking. The low pressure port therefore read a varying and incorrect pressure, and hence the associated DP was erroneous. The thread was galled between manufacture and the first test. It was considered that reasonable due care had been taken while transporting and installing this meter. Hence, there would be a considerable concern about the practicality of such a replaceable cone element design in typical industrial applications. The R&D project reverted to building fixed cone meter designs for the fourth iteration of tests.

5b.2 A Successful Hybrid Vortex / Cone DP Mass Meter Design

For the fourth design iteration a 4" 0.563β cone element meters were built with a 1D bluff body to cone apex spacing. For simplicity this prototype meter was a flangeless 'wafer style' meter (as shown in Figures 17 & 18). The inlet pressure tap and the downstream diagnostic pressure tap were on the upstream and downstream pipes respectively. The cone extended into the downstream pipe. This 4^{th} iteration 1D spacing ('short cone design') meter was tested with air flow at CEESI.

As a proof of concept test the test matrix was limited to two pressures. Figure 18 shows the meter installation. Note that unlike the drawing in Figure 17, the actual meter produced (Figure 18) 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.

Figure 19 shows the cone meter discharge coefficient vs. Reynolds number relationship fitted by a linear equation. This discharge coefficient was slightly lower than would be expected by a standard cone meter. However, the discharge coefficient across the tested range is not significantly outside of the accepted range for standard cone meters, i.e. 0.8 ±8% (i.e. $0.736 \leq C_d \leq 0.864$). Furthermore, this meter is not a standard cone meter, with an unconventional support bar. Hence, the calibration result is understandable, and 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 20 shows the calibration result of the vortex meter. A constant K-factor fitted the reference meter to 0.75% uncertainty. The mass flow rate prediction of the system is shown in Figure 21. The mass flow rate is predicted to within 1% and 95%. The volume flow rate prediction of the vortex meter is shown in Figure 22. The volume flow rate prediction is within 1% and 95% confidence. The density prediction of the system is shown in Figure 23. The density prediction is within 1.5% and 95% confidence.

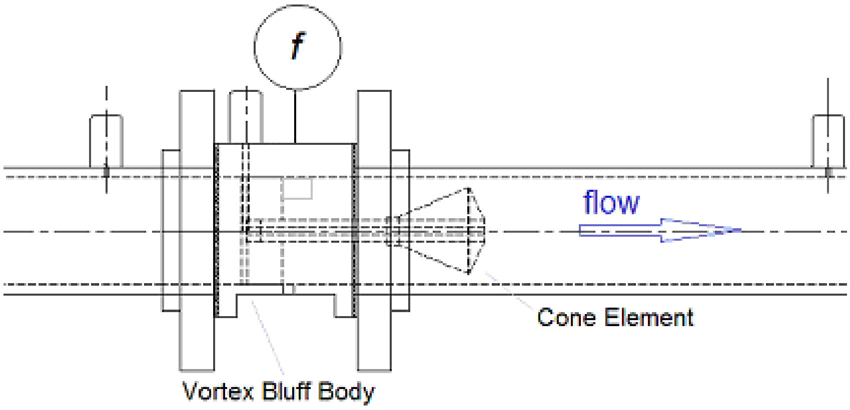

Fig. 17. Fourth Hybrid Vortex / Cone DP Meter Design

Fig 18. The Prototype Mass Meter Installed at CEESI.

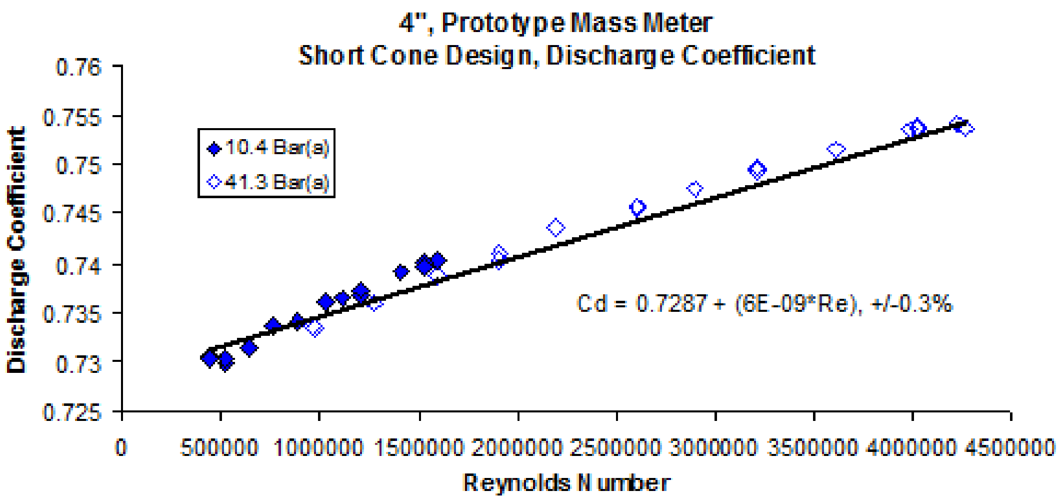

Fig 19. Discharge Coefficient Calibration of the 'Short Cone Design' Cone Meter.

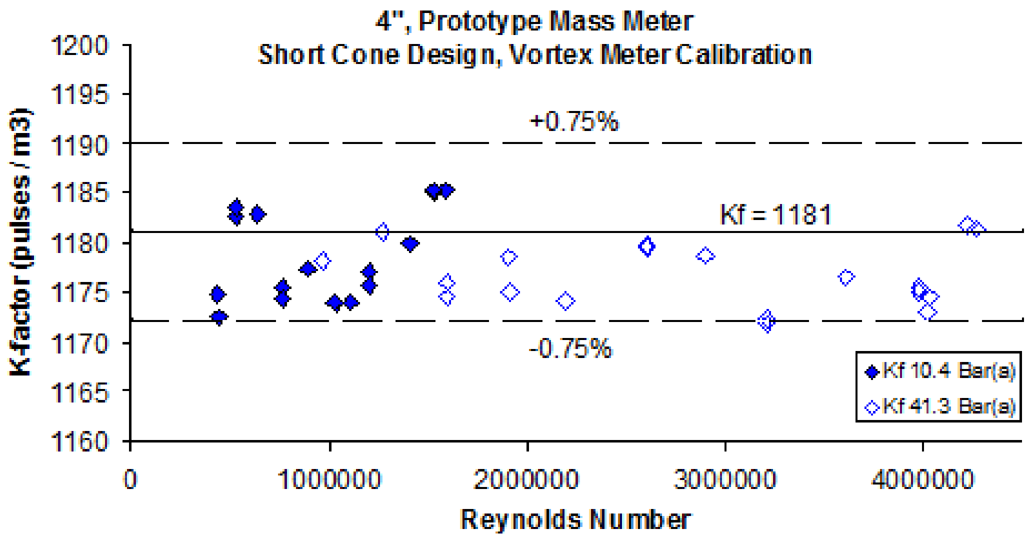

Figure 20. K-Factor Calibration of the 'Short Cone Design' Vortex Meter.

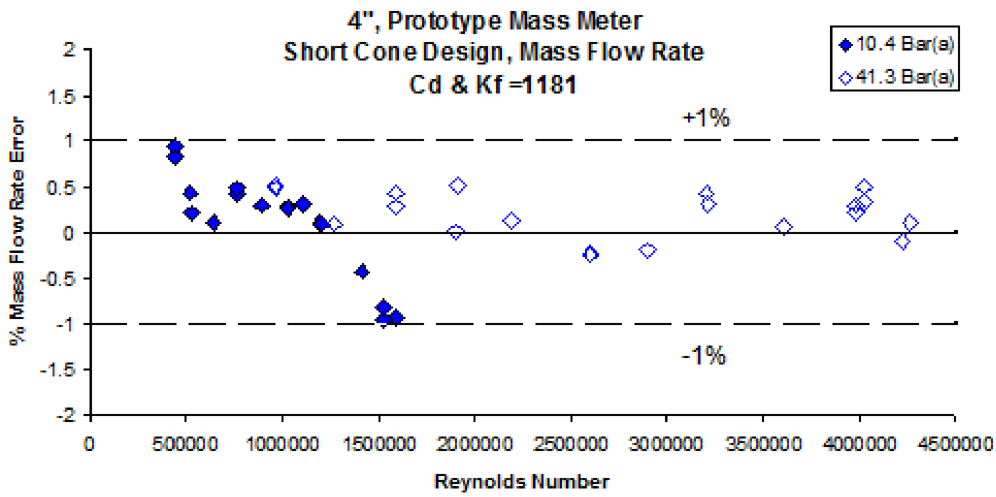

Fig 21. Mass Flow Rate Prediction by Combining Traditional Cone & Vortex Meters.

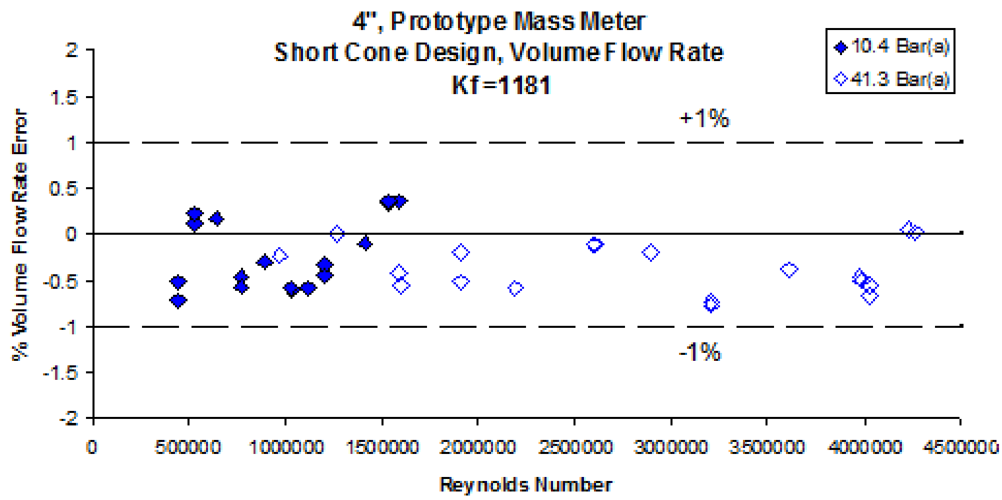

Fig 22. Vortex Meter Volume Flow Rate Prediction.

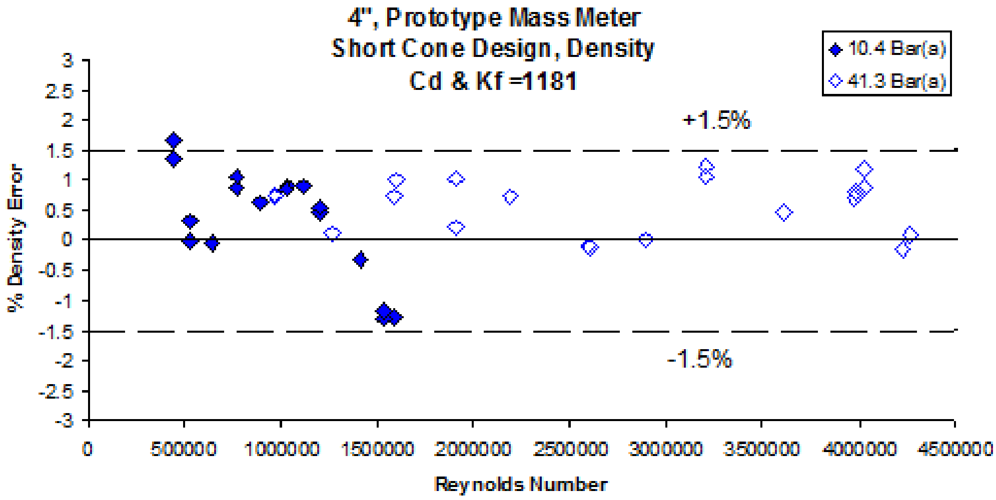

Fig 23. Density by Combining Traditional Cone & Vortex Meters.

6 A 2" Hybrid Vortex / Cone DP Mass Meter Steam Flow Test

In 2015 Vortek Instruments tested this prototype mass meter at the Spirax steam flow test facility in Cheltenham, UK. Steam flow test facilities are rare and the few that exist are generally private facilities not available for hire by third parties. A 2", 0.5β meter was built and tested with single phase saturated steam flow (see Figures 24 and 25). The dry gas saturated steam test data ranged between 4 & 10 Bar.

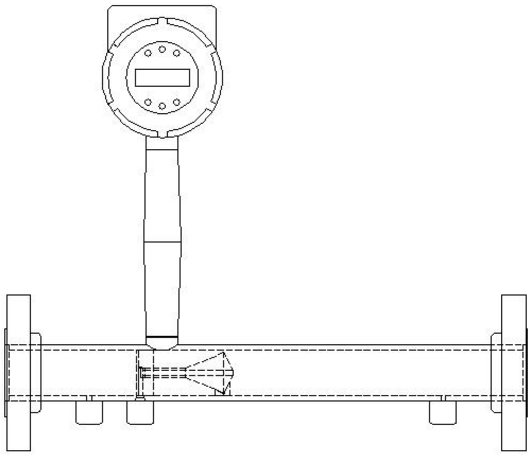

Fig. 24. 2" Vortex / Cone DP Mass Meter

The Spirax facility is a steam flow facility for general saturated steam flow component testing. However it was not primarily designed as a flow meter calibration facility. The steam flow rate reference was a vortex meter. The nominal volume flow uncertainty was 1%. Due to data logging issues between the facility control panel and the meter under test each test point's average reference flow rate was manually estimated and recorded from observing the facility control system output over time. It was assumed, but not guaranteed, that the steam maintained 100% quality. It is therefore conservatively estimated that the reference volume flowrate uncertainty was 2.5%, the reference steam density uncertainty was estimated at 1%, and therefore the corresponding mass flow rate uncertainty was estimated at 3%. It is not possible to give any instrument a lower uncertainty rating than the reference system on which it was calibrated. Hence, in this steam flow test, although steam flow is a rare and interesting flow meter test medium, the flow meter can only be shown to predict the mass flow to 3% uncertainty. This is a limitation of the specialized steam flow facility, and not necessarily the best performance of the meter under test.

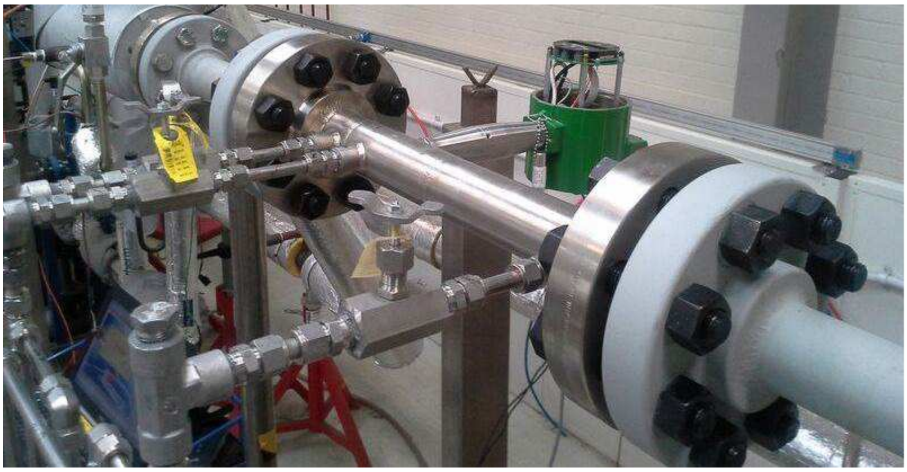

Figure 25. 2” Vortex / Cone DP Mass Meter at the Spirax Steam Test Facility.

Figure 26 shows the cone DP meter’s discharge coefficient plotted against Reynolds number. A constant discharge coefficient fitted the data to 1.4%. Figure 27 shows the vortex meter K-factor plotted against average gas velocity. A constant K-factor fitted the data to 0.9%. (These values would be reduced if the meter was calibrated on a single phase gas flow calibration facility.) The relatively high uncertainty of the paired meter calibrations will have an adverse effect on the density and mass prediction.

Figure 28 shows the percentage difference between the vortex meter’s predicted and reference volume flow rate. The error bars represent the volume flow rate reference uncertainty. The meter under test predicts the volume flow rate to within 1% of the reference. Figure 29 shows the percentage difference between the meter under test’s predicted and reference mass flow rate. The error bars represent the mass flow rate reference uncertainty. The meter under test predicts the mass flow rate to 3% of the reference meter. Figure 30 shows the percentage difference between the meter under test’s predicted and reference fluid density. The error bars represent the reference density uncertainty. The system predicts the fluid density to within 3% of the reference. Due to the nature of the steam test facility and the available reference uncertainties during this test, these results are as good as could be expected. This mass meter design has predicted the volume and mass flow rates to the same uncertainty as the available reference data.

Vortek Instruments, DP Diagnostics (and Swinton Technology) also tested the DP meter diagnostic system ‘Prognosis’ during these steam tests. The extra downstream pressure port required by the DP meter diagnostic system is evident in Figure 25. Furthermore, the metering system was also tested with wet saturated steam. However, these research topics are out with the scope of this paper and would require a separate dedicated paper to discuss.

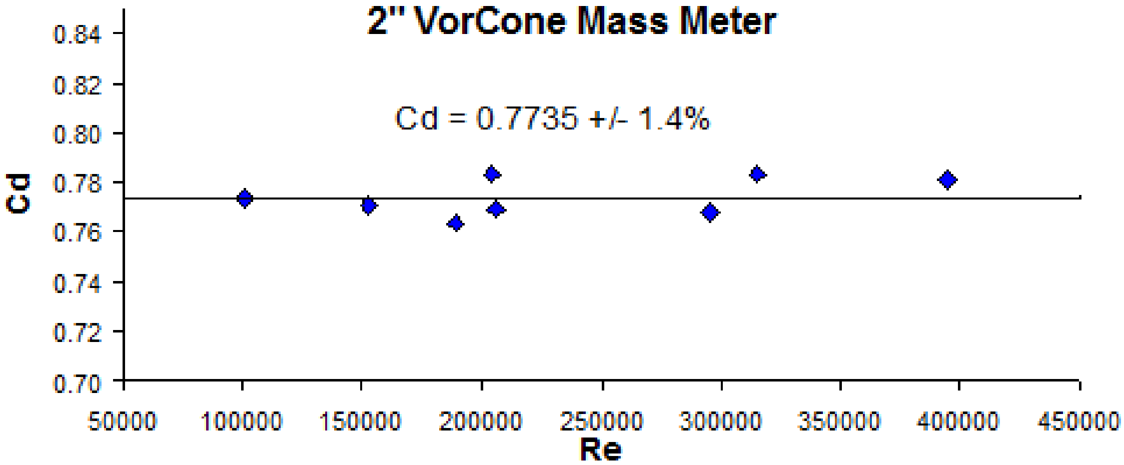

Figure 26. Cone Meter Cd vs. Reynolds Number Calibration Data

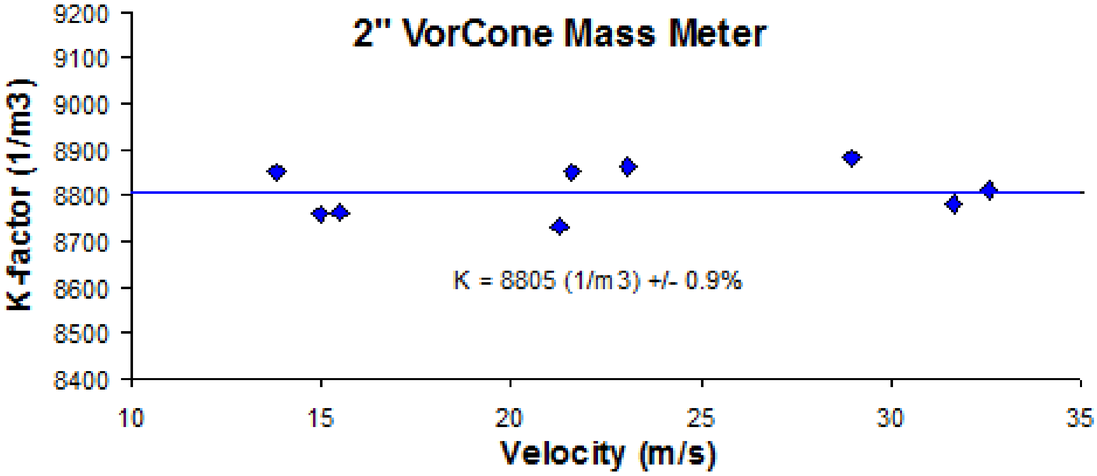

Figure 27. Vortex Meter K-factor vs. Gas Velocity Calibration Data

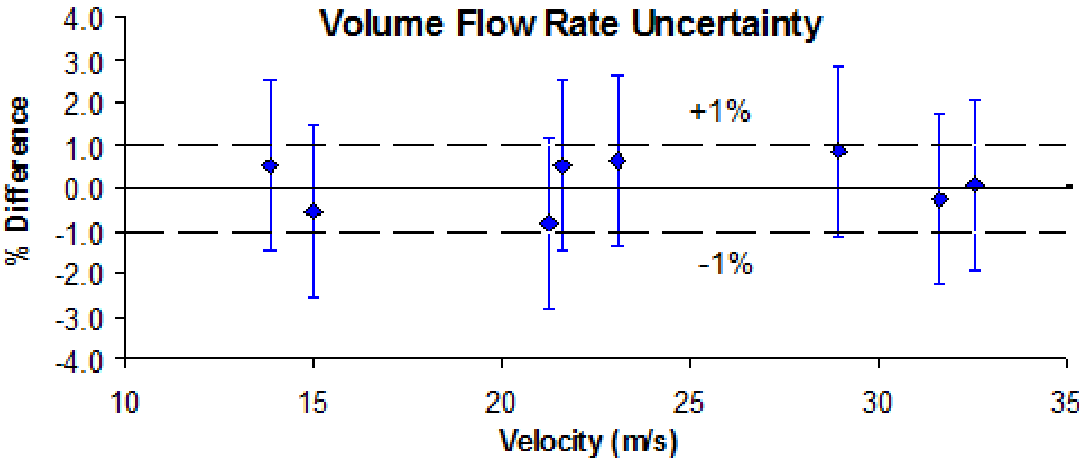

Figure 28. Volume Flow Rate Prediction vs. Reference Meter Data

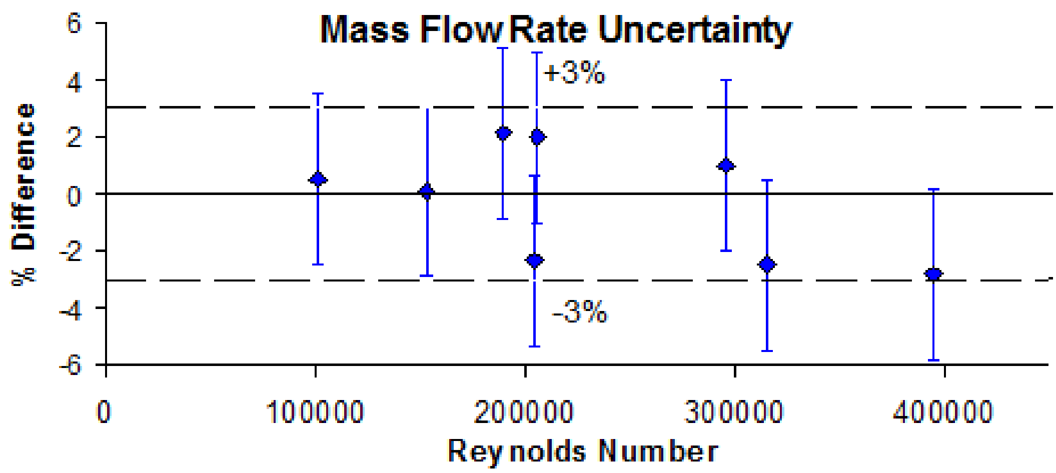

Fig 29. Mass Flow Rate Prediction vs. Reference Meter

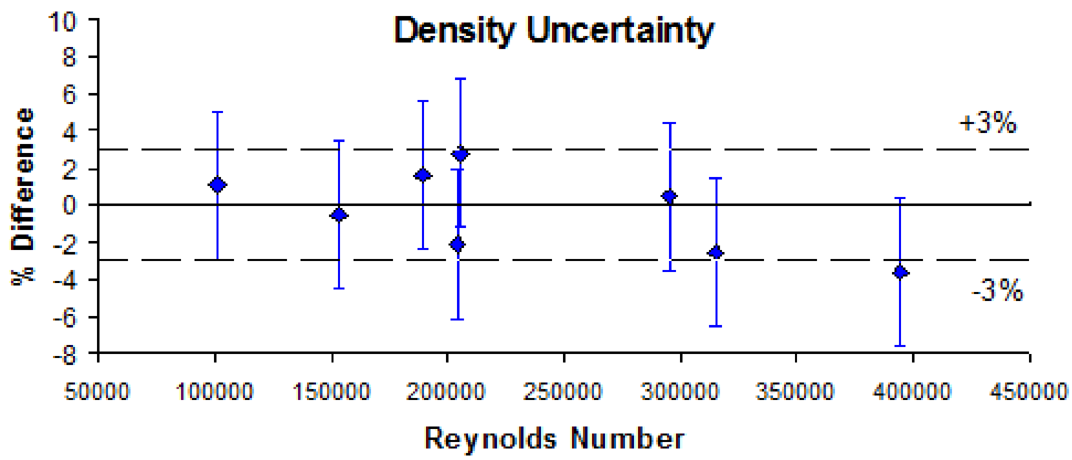

Fig 30. Density Prediction vs. Reference Value

7. 3" Hybrid Vortex / Cone DP Mass Meter Tested with Water & Air Flows

A 3" 0.68β mass meter was manufactured. (This meter was sized for an industrial steam flow application field test.) A drawing of the meter is shown in Figure 31. The vortex shedding sensor is again positioned 180^0 to the pressure ports to avoid sensor mounting congestion. This meter was first tested with water flow at Vortek Instruments. No photograph of this test was taken, although Figure 31 also shows a photograph of a later 2" meter of the same design being water flow tested in the same facility.

The Vortek Instrument water flow facility utilizes a weigh tank and has a mass flow rate uncertainty of 0.1%, a water density uncertainty of 0.05%, and a volume flow rate uncertainty 0.12%. Figures 32 & 33 show the cone DP & vortex meter water flow calibration data respectively. Figure 34 shows the resulting density prediction and volume & mass flow rate predictions. This mass meter technique is applicable to liquid or gas flow applications, and here when the metering system has been calibrated on a very low uncertainty water flow facility the meter outputs also have a corresponding low uncertainty.

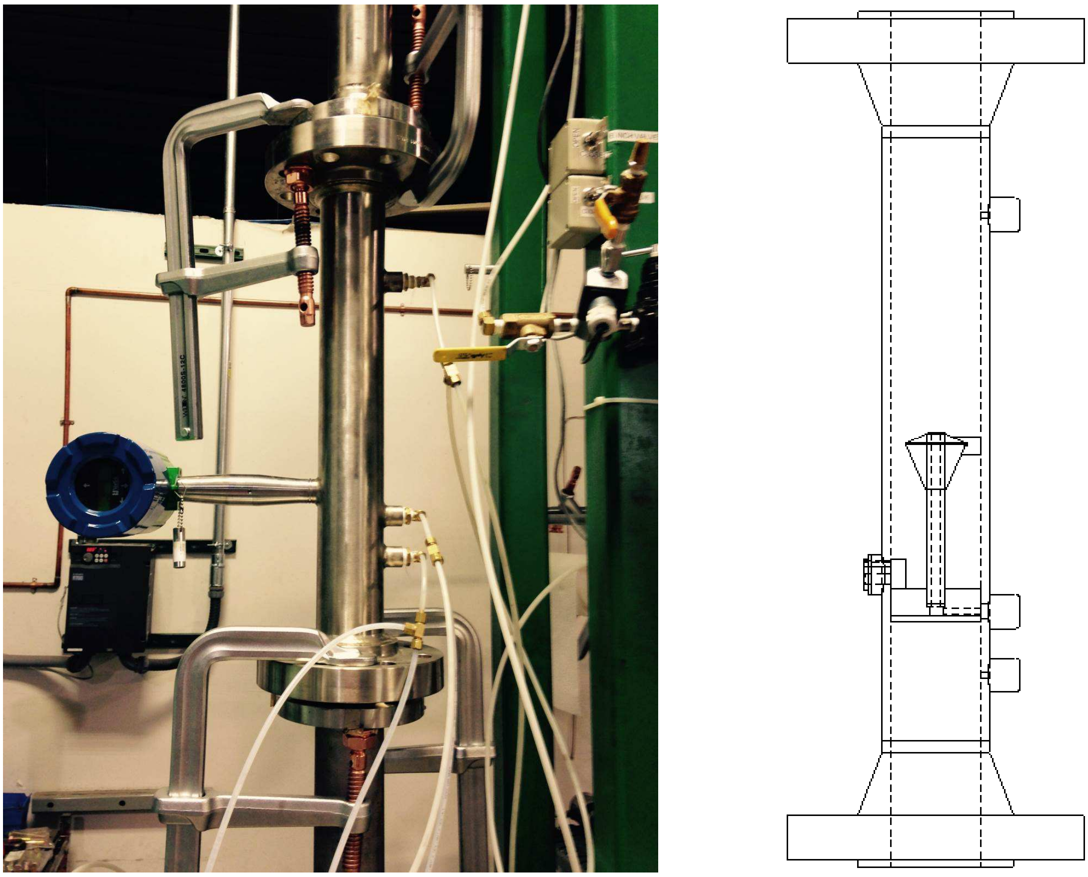

Fig. 31. 3” 0.68β Meter Drawing & a 2”, 0.5β at Vortek Water Facility

This 3” meter was also extensively air flow tested at CEESI. The air test matrix had three pressures nominally of 56 Bara (812 psia), 27.6 Bara (400 psia) & 10.4 Bar (150 psi), which relate to three nominal gas densities 66.7, 33.0 & 12.3 kg/m^3. The Reynolds number range was 3.4e5 < Re < 6.2e6, while the gas velocity range was 5 $<U_1(m/s)<$ 30. The cone DP meter discharge coefficient data and the data fit are shown in Figure 37. The vortex meter K-factor data and the data fit to average gas velocity are shown in Figure 37. The K-factor is seen to be very steady at high to moderate velocities, although it begins to become non-linear at < 7 m/s. This result was in part due to an over-sight during the testing. The vortex meter was inadvertently operated without the standard signal filtering system activated. This filter helps signal analysis by filtering out signal noise. Such noise filtration is usually most beneficial at lower velocities. This lack of the standard practice noise filtering accounts for at least some of the perceived K-factor non-linearity at lower velocities. A data fit was therefore preferred over a constant K-factor.

Figure 38 shows the gas mass flow rate prediction uncertainty. (The uncertainty bars represent the reference mass flow rate uncertainty of 0.35%). The mass flow rate is predicted to 1% at 95% confidence. Figure 39 shows the volume flow rate prediction uncertainty. (The uncertainty bars represent the reference volume flow rate uncertainty of 0.3%). The volume flow rate is predicted to 1% at 95% confidence. Figure 40 shows the gas density prediction uncertainty. The gas density is predicted to < 2% at 95% confidence.

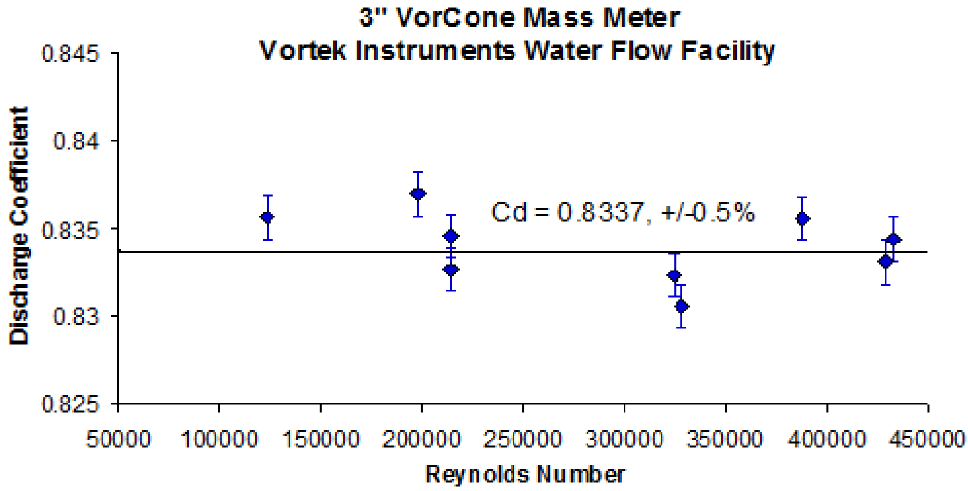

Fig 32. 3” Vortex / Cone DP Meter DP Meter Water Calibration Result

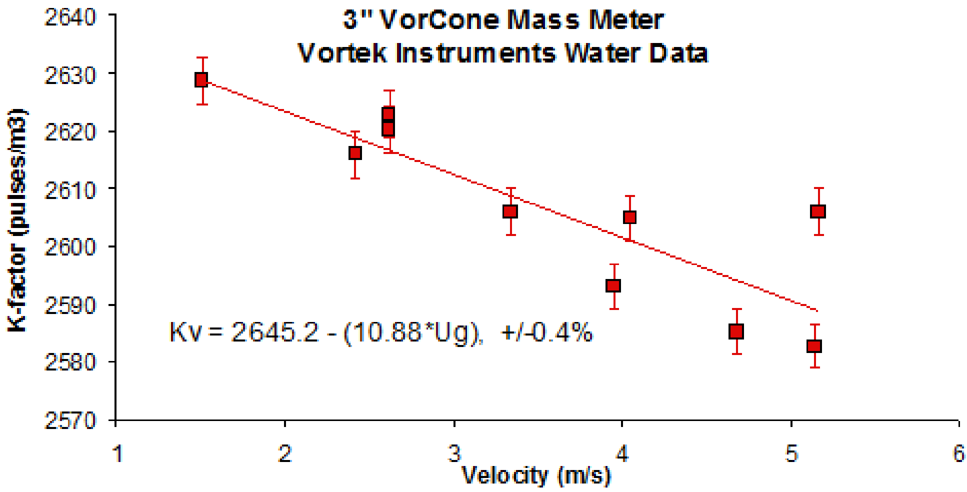

Fig 33. 3” Vortex / Cone DP Meter Vortex Meter Water Calibration Result

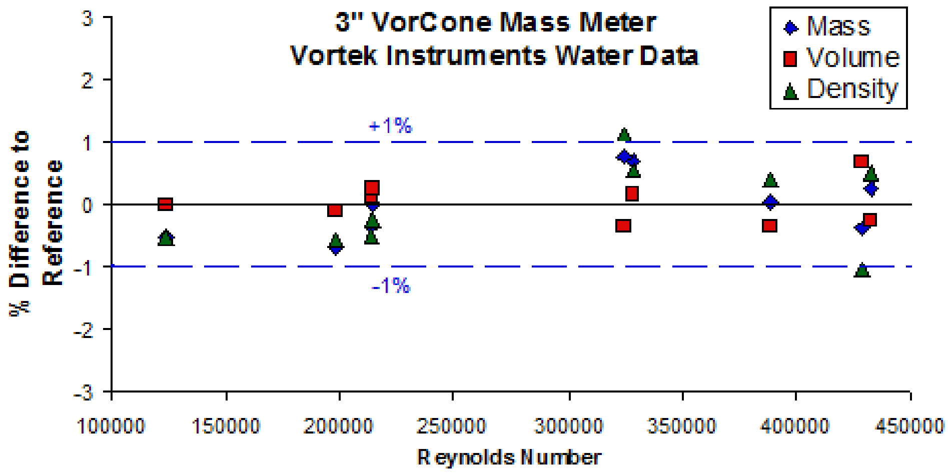

Fig 34. 3” Vortex / Cone DP Meter Water Density, Volume Flow & Mass Flow Prediction Result

Fig 35. 3” 0.68β Hybrid Vortex / Cone DP Meter Under Air Flow Testing at CEESI.

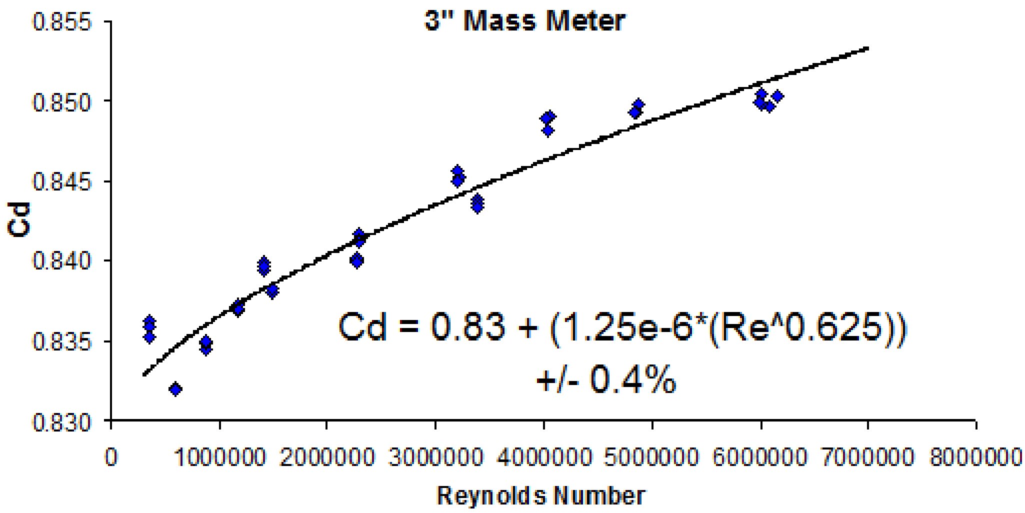

Fig 36. 3” Cone DP Meter Discharge Coefficint vs. Reynolds Number Air Data.

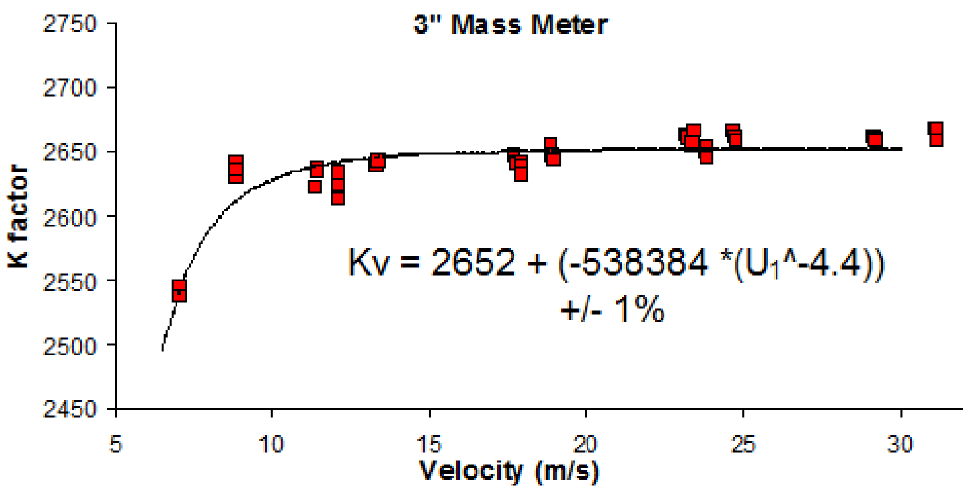

Fig 37. 3” Vortex Meter K-Factor vs. Gas Velocity Air Data.

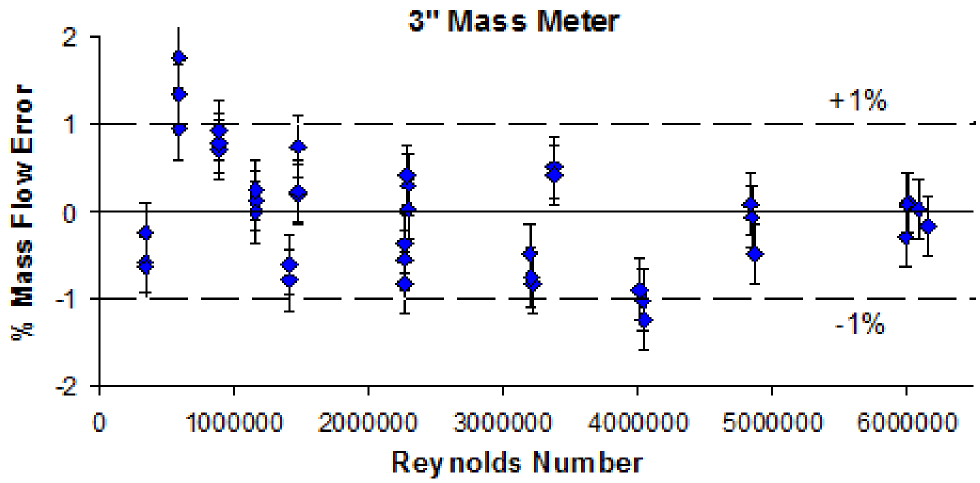

Fig 38. 3” Mass Meter Mass Flow Rate Prediction Uncertainty with Air Flow.

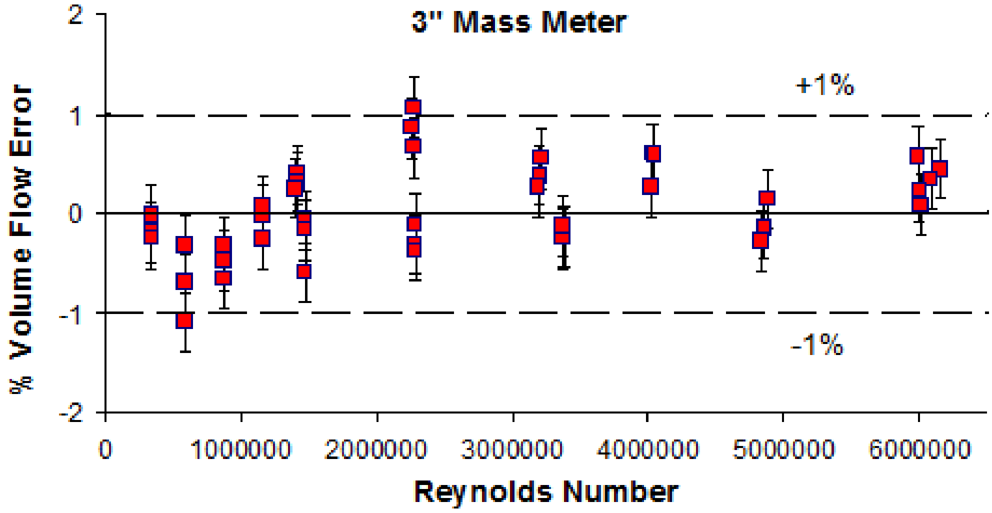

Fig 39. 3” Mass Meter Volume Flow Rate Prediction Uncertainty with Air Flow.

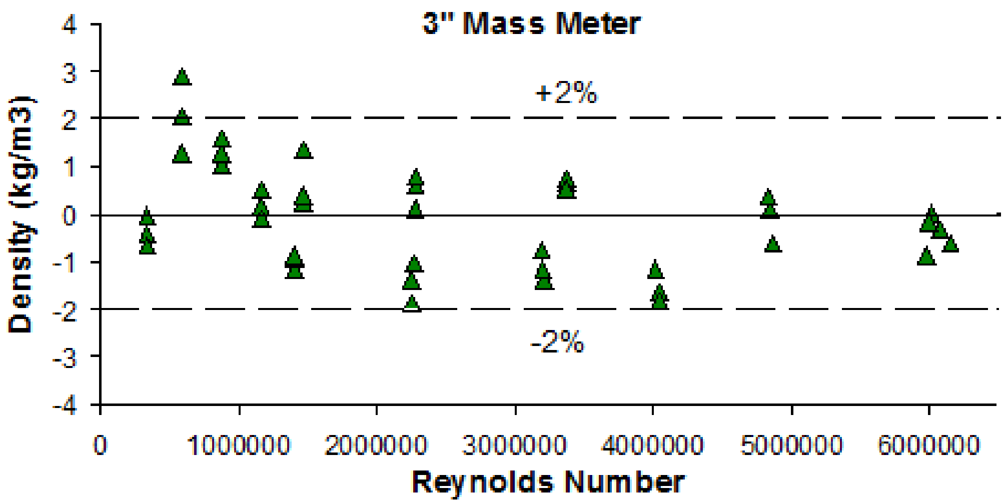

Fig 40. 3” Mass Meter Gas Density Prediction Uncertainty with Air Flow.

7.1 3" Hybrid Vortex / Cone DP Mass Meter Combined Gas & Liquid Data

Figure 41 shows cone DP meter discharge coefficient derived from the combined data from the gas and water labs. The two different labs give very similar discharge coefficients across the same Reynolds number range. Where the water and air Reynolds number ranges over-lap the discharge coefficients agree.

Note that due to the low Reynolds number range of the water data a constant discharge coefficient fitted this range well (see Figure 32). However, if we were to have extrapolated the water calibration result to the much higher Reynolds number values of the gas flow Figure 41 shows that a significant discharge coefficient bias would have been introduced. Only by calibrating across an applications full Reynolds number range can the operator be assured that the discharge coefficient data fit is applicable for that Reynolds number range. When combining the water and air calibration data one linear discharge coefficient vs. Reynolds number data fit predicts the discharge coefficient across both data sets to 0.5%.

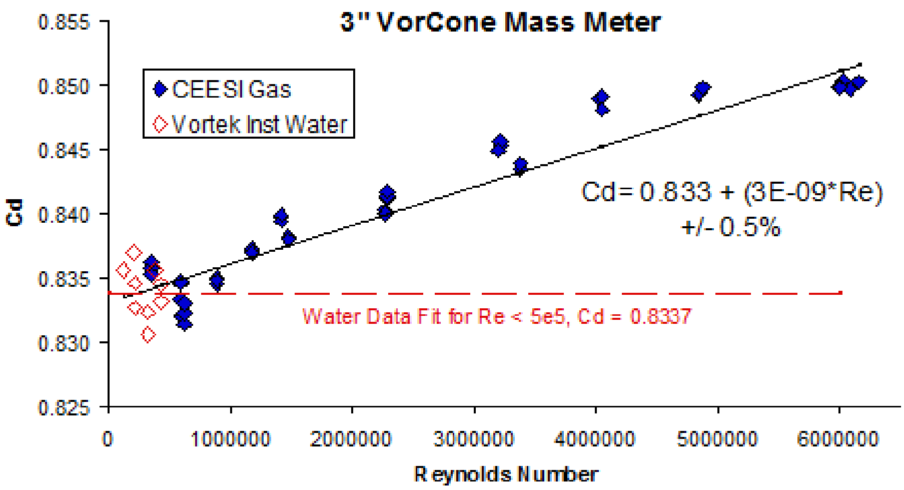

Fig 41. Air & Water Cone Meter Discharge Coefficient Calibration Data Set & Data Fit

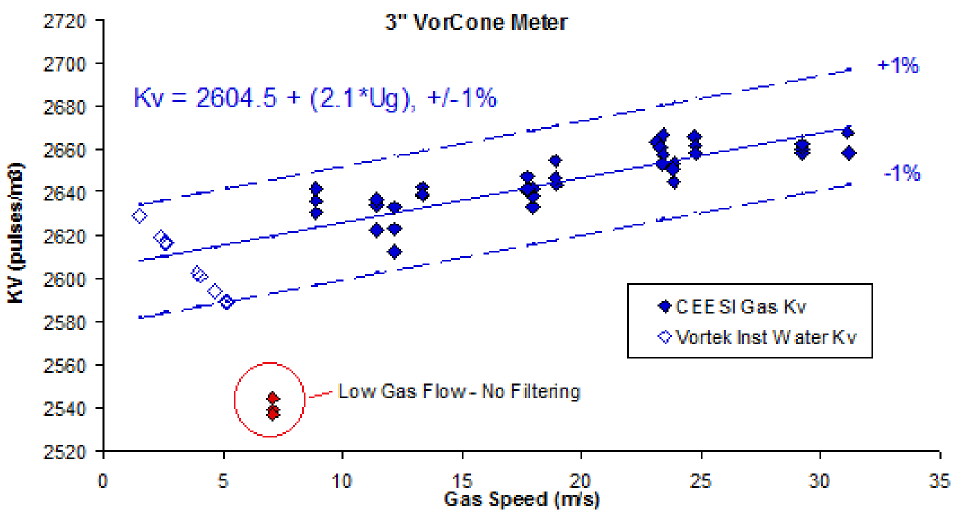

Fig 42. Gas & Water Lab Vortex Meter K-Factor Coefficient Data Set & Data Fit

Figure 42 shows the vortex meter K-factor derived from the combined data from the gas and water labs. If the low air flow velocity result is ignored (as it has been shifted due to the lack of noise filtering) the two different labs give very similar K-factors across the same Reynolds number range. One linear K-factor vs. velocity data fit predicts the K-factor across both data sets to 1%.

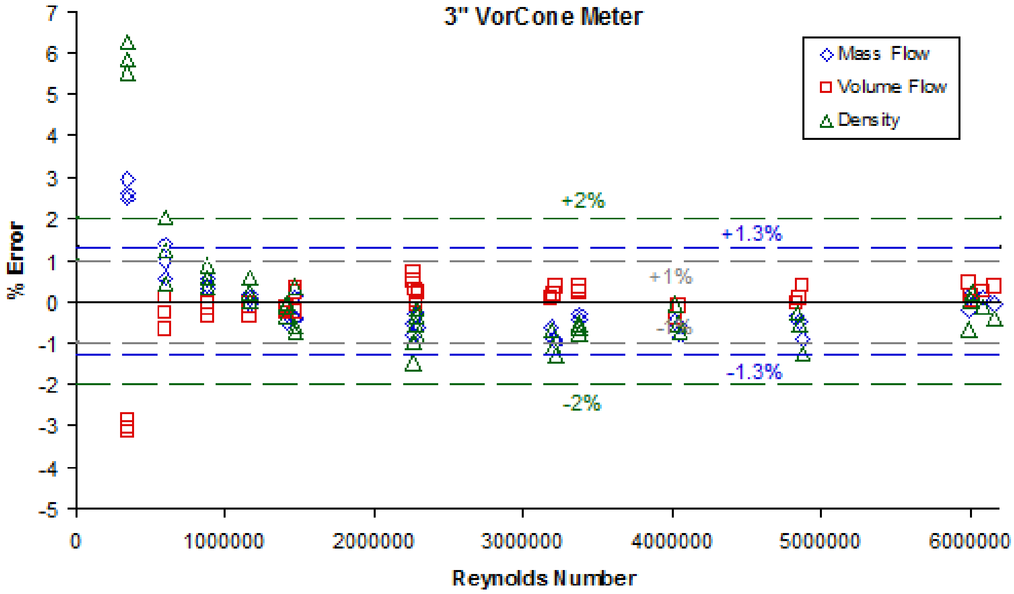

Fig 43. Combined Gas & Water Lab VorCone Mass Meter
Mass Flow, Volume Flow & Density Predictions

In practice operators nearly always know enough about their process that they will know the fluid type they are metering. As such, it is not a realistic example to show this mass meters ability to measure the gas and liquid flow ranges using the combined water & air calibration data. Furthermore, prior knowledge of whether the application has a gas or liquid flow dictates if the flow calculation applies expansibility on the cone DP meter calculation, and the fluid viscosity input. However, in order to show this mass meter's range ability, i.e. wide applicability, Figure 43 shows the meter's performance when applying the combined calibration factors shown in Figures 41 & 42. In these calculations, the gas data had the expansibility correction applied and the air and water data had the appropriate fluid viscosity applied to the discharge coefficient calculation. The range in flow conditions in this combined data set is extreme, with a density range between water and low pressure air of 82:1, and volume and mass flow ranges (i.e. turn downs) of 20:1 and 59:1 respectively.

Figure 43 shows the predicted mass flow, volume flow, and fluid density from the combined water and gas calibration data fits. Whereas as a liquid meter or a gas meter the system predicted the mass and volume flows to 1%, and the density to 2% at 95% confidence, applying the meter across the combined air and water flow ranges produces only a marginal increase in uncertainty. Figure 43 shows the performance across both fluids and their respective ranges was the mass flow to 1.3%, volume flow to 1%, and the density to 2% at 95% confidence. (The few points outside these limits are the low velocity gas flow where the vortex meter had no noise filtering activated.)

8 CONCLUSIONS

Traditional gas flow meter designs such as ultrasonic, turbine, vortex and DP meters require that the gas density, and possibly viscosity and isentropic exponent, be supplied from an external source in order to predict the mass flow rate (or the equivalent volume flow rate at standard conditions). The gas viscosity and isentropic exponent can usually be estimated to reasonable uncertainty. Furthermore, the meter output tends to have a relatively low sensitivity to these two parameters. However, the requirement for fluid density can be more problematic. The uncertainty in a traditional meter's mass flow rate prediction is heavily influenced by the density prediction uncertainty. Density uncertainty is a significant (and sometimes primary) contributor to traditional mass flow rate prediction uncertainty. As such, direct mass measurement is sometimes beneficial, either to eliminate the requirement for density measurement or to act as a check against the independent density measurement.

While Coriolis meters are large by volume (footprint) and weight, have high permanent pressure loss and are relatively expensive, for clean high value liquid flows their exceptional measurement performance has established them as the benchmark of mass flow and density metering. However, Coriolis meter performance declines somewhat with gas flow. Although still a good meter the Coriolis meter does not measure density of low pressure gas (the output is called an indication and not a measurement), and the gas mass flow rate uncertainty increases to be equivalent to standard gas meters. This reduction in the main pro, i.e. performance, coupled with the continued existence of the cons, i.e. size and weight issues, high permanent pressure loss and expense, has meant that Coriolis meters are less favoured for many gas applications, especially moderate to low pressure flows where the value of the product is less. There is therefore still a niche market need for a simple, relatively inexpensive gas mass flow meter.

The simple Boden mass flow meter concept has been known for sixty years. The concept historically failed to become a mainstream meter design due to various reasons, including early computer limitations and practical problems in combining the two technologies. As such the concept remained relatively obscure. However, modern computers easily cope with the demands of this technology and the practical problems of combining the flow meter technologies are surmountable.

DP Diagnostics and Vortek Instruments have developed a practical Boden type mass flow meter by combining a vortex meter and a cone DP meter. Multiple meter tests have shown this hybrid meter design to be a viable practical industrial gas mass meter. This particular design allows the vortex and DP meter sub-systems to be independently sized. Critically, this allows both meters to be sized for use across the same flow ranges thereby solving one of the most challenging problems that hampered the R&D of this general concept for many years. The research and development project has solved the mechanical and fluid mechanics problems arising from creating this hybrid metering system.

The mass meter system has now been tested in three different test facilities with air, water and steam. The results show that when tested at a reputable flow calibration test facility across the applications full Reynolds number range, the technology can meter even low pressure gas flows to 1% by mass and 1% by volume while measuring the fluid density to

< 2%. The system can be used as a stand-alone meter, or in conjunction with a density measurement system. If a density measurement is independently available both the cone DP meter and the vortex meter can use the independent density prediction to individually measure the mass flow rate. The combination of the two meters supplies a density measurement check independent of the traditional density measurement.

9 REFERENCES

1. Boden., "Mass Flow Meter" US Patent No. 2772567A, Granted 1956.

2. Pfrehm. "Modified Turbine Mass Flow Meter", US Patent No. 3430489, Filed 1967.

3. Lisi, E.L., "Mass Flow Meter", United States Patent No. 3,785,204, Filed April 6th, 1972, Awarded January 15th, 1974.

4. Mottram, R.C., "Mass Flow Meter", United Kingdom Patent Application No. GB 2161941A, Filed 19th July 1984.

5. DiMarco S et al "Simplified Fluid Property Measurement", US Patent No. 7258024 B2, Filed March 2005.

6. Steven R., "Flow metering", US Patent No. 2010/0224009 A1, Published Sept. 2010.

7. Storer, J., "Flow Measurement Utilizing Vortex Shedding Meters", International School of Hydrocarbon Measurement, Norman, Oklahoma, May 22nd -24th, 1990.

8. Storer, J. "Advances in Vortex Shedding Flow Metering", International Symposium of Fluid Flow Measurement, Anchorage, Alaska, August 2009.

9. Stewart D., Reader Harris M., Peters R., "Derivation of an Expansibility Factor for the V-Cone Meter", Flow Measurement International Conference, Peebles, Scotland, UK, June 2001.